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ECONOMICAL SPACE POWER SYSTEMS

by Joel H. Burkholder

Solarex Corporation
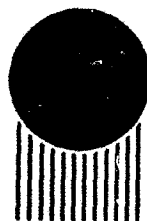
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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

NASA Lewis Research Center

Contract NAS3-21353

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16. Abstract

This study investigates a commercial approach to design and fabrication of an economical space power system. With the advent of the space shuttle, steps can be taken to back away from the presently used space qualified approach in order to reduce cost of space hardware by incorporating commercial design, fabrication and quality assurance methods. Cost projections are based on a 2 kW space power system conceptual design taking into consideration the capability for serviceability, constraints of operation in space and commercial production engineering approaches. A breakdown of the system design, documentation, fabrication and reliability and quality assurance estimated costs are detailed.

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1.0 INTRODUCTION

1.1 Purpose of Study

NASA's proposed space programs over the next decade indicate that substantial increases in space power will be required. Because of the high cost associated with traditional space qualified systems, the consideration of employing more economical approaches becomes more topical.

With the advent of the space shuttle, substantial cost savings can be realized. Economic systems studies indicate that with the space shuttle substantial cost reductions can result through the application of repairing and refurbishing of non-functional satellites. Even with present traditional space qualified approaches the cost savings may be substantial because of the capability of reusing systems and components which was previously un-achievable.[1,2]

With the concept of systems maintainability, an alternate approach to traditional space qualified practices becomes possible. Historically, space quality has implied systems that required continuous reliable functioning over a given span of time. [Such rigorous requirements have resulted in the evolution of highly detailed and costly adherence to quality, assurance at all levels of design, fabrication, and deployment of such systems.] Based on the assumption that future power systems have the option for servicing,

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an opportunity for scaling down from present space quali-
fied standards could be possible.

1.2 Approach to Study

This study comprises a three part investigation which
identifies those methods, practices and tradeoffs generated
by a commercial organization given the task of estimating
the cost and effort levels associated with producing a
space power system. A summary description of each task
follows:

Task I - <u>Conceptual Design</u> - Produce a conceptual design
of a 2kW continuous load space power system in
sufficient detail to identify all major com-
ponents and performance specifications.

Task II - <u>Approach to Design, Documentation, Fabrication
and R&QA</u> - Document the practices, procedures,
manpower, cost and organizational structures
proposed for design and fabrication of the
system. This task is broken into four sub-areas
of Design, Documentation, Fabrication and R&QA.

Task III- <u>Cost Summary and Analysis</u> - Summarize and
evaluate the cost and manpower information
derived from Task II and analyze the impacts
of servicing, warranty and single versus multiple
units on cost.

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2.0 CONCEPTUAL DESIGN (TASK 1)

2.1 System Description

The power system design required a conceptual design at the functional block level. Major components to be included in this design were battery chargers, batteries, solar array, power regulator, and array drives.

2.1.1 Launch and Mission Type

- Launch - Shuttle - Eastern Test Range
- Mission - Free Flyer - unattached orbital vehicle capable of independent operation

2.1.2 Orbital Characteristics

- Low earth orbit (LEO) - @ 370KM, 28.5° inclination
- Orbital period - 93 minutes; 57 minutes illuminated, 36 minutes eclipsed.

2.1.3 Launch Constraints

- Volume - $33m^3$
- Shape - cylindrical 3m x 3.75m diameter

2.1.4 System Electrical Characteristics

- Power source -- solar arrays, deployable/retractable
- Power level - 2kW continuous load @ BOL
- Distribution voltage - 28±5VDC, unregulated
- Energy storage - Batteries
- Battery discharge depth - 25%
- Electro-Mechanical System - 2 axis solar array drive
- Design life - 4 years

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2.1.5 Launch Environment

The system launch environment will sustain the following conditions:

- Temperature - Slow steady rise from $21^{\circ}C$ (294K) to $27^{\circ}C$ (300K) within the payload bay.
- Pressure - Payload bay pressure reduces to space pressure within 90 seconds after liftoff.
- Return environment - maximum temperature in the shuttle bay of $160^{\circ}F$ and 2.8G.
- Vibration characteristics - $0.1G^2$/Hertz acceleration spectral density, 7.31 RMS for a duration of 30 seconds over a range of 60 to 300 Hertz. Vibration acceleration increases from $0.01G^2$/Hertz at 15 Hertz rate of 6dB/octave to 0.1G/Hertz at 60 Hertz and decreases at a similar rate from 300 to 1000 Hertz.
- Sound pressure - 145d/B over a range of 20 to 10,000 Hertz for a duration of 90 seconds.
- Acceleration - steady state in the X axis @ 3.3G with transients between 5-10 Hertz at 1.0 inch double amplitude, 10-21 Hertz at 5.0G and 21-35 Hertz at 1.0G.

2.2 Solarex Conceptual Design

The system design described in this section was selected to take advantage of the standard Solarex 5cm x 5cm commercial grade solar cell (see Figure 2-1). The cell efficiency specification was set at $\geq$14% AM1. Based on this specification the solar array's design and sizing was performed.

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Figure 2-1

Schematic of 5cm x 5 cm Space Solar Cell

Major Features:

- N^+ - P silicon Solar Cell
- 10 ohm-cm silicon
- Thickness -- 250mm
- ti-Pd-Ag Contacts
- ta05 Antireflection Coating

2.2.1 Solar Array Design

The solar array design employs an array adequate to
generate 2kW continuous to load plus additional sizing to
charge batteries and take into account the effects of the
space environment. Calculations performed in the array
sizing effort were based on the parameters given in Table 2-1
(Electrical Power Specification Parameters) and the array
simulation equations in Table 2-2. The cell's I_{mp} and V_{mp} at
EOL was based on a 10 ohm-cm resistive silicon base material at
.030 cm thickness with a microsheet cover of .015 cm using a
1Mev-cm^2 radiation profile for a 370 kilometer orbit at
28.5° inclination[3] (see Table 2-3). Similarly, voltage drops
across the blocking diode and power regulator (V_d) and resis-
tance of the wiring were based on estimated voltage losses
and resistance levels typical of the systems. Battery cycle
efficiency (σ_k) and voltage drop across the slip rings were
based on estimates obtained and corroborated by several sources
(Appendix A). All other parameters used were given by the Con-
tract's Specification. The model incorporating these inputs
was then formulated (Table 2-2). The underlying assumptions
which characterize these equations are as follows.

- The onset and offset of sunlight was considered
  instantaneous.

- The flux of sunlight during time in the sun was
  constant.

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Table 2-1

ELECTRICAL POWER SPECIFICATION PARAMETERS

Symbol	Description	Value
V_{mp}	Voltage @ Max. Power Point	.386 VDC @ 60°C/EOL
I_{mp}	Current @ Max. Power Point	.822 Amp. EOL
R_w	Resistance of Wiring	.01 ohms
V_d	Voltage drop across blocking diode and Power Regulator	.2 VDC.
σ_b	Battery Cycle Efficiency	78% (range =75%-80%)
P_1	Power to Load	2 kW
V_1	Voltage to Load	28 $\pm$ 5 VDC
V_s	Voltage Drop Across Slip Ri	.2VDC
T_2-T_1	Time in Su.-Time in Eclipse	57 min - 36 min

Table 2-2

Computer Simulation Model

Load Current = $I_p = P_L/V_L$

Battery Energy Yield = $P_b = T_2 P_L /T_1 \sigma_\beta$

Array Current = $I_b = (P_b + P_L)/V_L$

Voltage Loss/Wiring = $V_w = R_w \cdot I_b$

Array Voltage V_a = $V_a = V_L + V_s + V_d + V_w$

Array Power Output = $Pa = I_b \cdot V_a$

Number of Parallel Strings = $N_p = I_b /Imp$

Number of Cells in Series =

$$N_s = Va/Vmp$$

Total Number of Cells = Nc = Np . Ns

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Table 2-3

Estimated Effect of Radiation on Solarex Photovoltaic Cell Performance

Year	Output at Maximum Power Point	Percent of Initial Output
0	Current	100.0
	Voltage	100.0
1	Current	99.7
	Voltage	99.3
2	Current	98.7
	Voltage	98.6
3	Current	98.2
	Voltage	98.4
4	Current	97.9
	Voltage	98.0

Where:
1. 10 ohm-cm Resistive Silicon
2. .030 cm Thick Silicon Wafer
3. .015 cm Microsheet Cover-slip
4. Anti-Reflective Coating
5. Orbit: $\sim$ 370 KM Altitude
   28° Inclination

- The charge and discharge rates for the batteries
  were constant. No accounting for impedance changes
  or memory effects due to aging of the battery was made.
- No adjustment for transient power losses due to
  shadowing was made.

Using these equations a system sizing was performed for
both Beginning of Life (BOL) and End of Life (EOL). Using
the EOL sizing (see Table 2-4) further sizing was undertaken
to a) account for anticipated performance losses from cell
string open circuit losses due to thermal cycling and micro-
meteorites, and b) to arrive at a wing design that would
take advantage of the 5cm x 5cm cell and series string panel
approach. The major features of this final sizing effort
are given in Tables 2-5 and Figure 2-2 respectively.

In reference to the first item (a) in the preceeding
paragraph, further study was conducted to evaluate the relia-
bility characteristics of an array design using a simple
series (and shunt diode combination) string panel approach
common to a Solarex commercial panel. For this purpose a
simulation program was developed to evaluate this approach.
Some of the basic assumptions made for this exercise were:

- The solar cells were mounted with ceria doped
  microsheet coverslides.
- Interconnects would have stress relief to compensate
  for thermal cycling.

Table 2-4

Predicted Array Sizing for BOL and EOL^T

Category	BOL	EOL$^{**}_{*}$
No. of Cells/Series Strings	92	94
No. Parallel Strings	132	135
Total Number Cells Required	12144	12690
Power of the Array	3998.7w	3998.7w

T Estimated @ 60°C (333K) Peak temperature in Low Earth Orbit

*   Including added 1MeV/cm^2 radiation dosage after four (4) years @ 370 KM, 28° inclination.

**   Assuming a worst case I_{mp} - V_{mp} thermal degradation of 2.1mW/K.

Table 2-5

.Final Solar Cell Array Specification

- 144 Strings of 96 cells in series

- Each cell 5cm x 5cm plus 1mm non-overlapping bus

- Total cell area = 5.1cm x 5.1cm = 26.01cm^2

- Each cell string area = 249cm^2

- Width of each cell wing array = 247cm

- Total number of 5cm x 5cm cells = 13824

- Number of cells on each of two extendable
  Arrays = 6912 cells

- Each wing has 72 panels on it. Each panel
  contains one series string of 96 cells with
  shunt diodes across each string of 4 cells

- Each wing is 6 panels (1 string/panel) in
  width by 12 panels long -- a distance of 7.4 meters

- Each panel which carries a string of 96 cells
  is connected in parallel with every other panel
  on each wing

- Each of the two wing arrays carry 72 panels each,
  18.2M^2 for each wing area.

Figure 2-2

ARRAY WING CONFIGURATION

- Array Wing Features

  - 72 Panels/Wing

  - 6912 Cells/Wing

  - 8.9% Oversized

- Overall Array % Active Area = 95%

- Panel Features

  - One Series String of 96 Cells/Panel

  - 3mm Panel to Panel Spacing for Array Frame

  - 1mm x 1mm Intercell Spacing Between Active Areas

61.2cm

40.8cm

738.3cm.

246.7cm
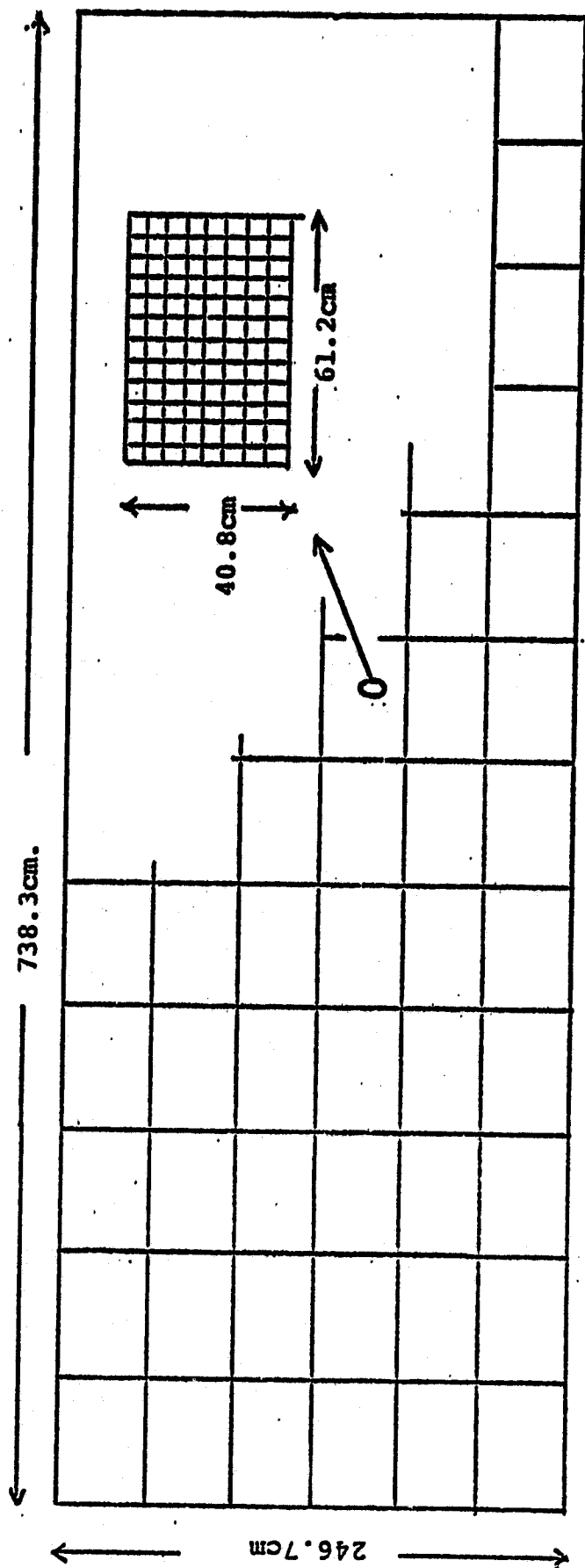
The study investigated three levels of failure rate by three solar cell/shunt diode ratios (i.e., 2:1,6:1,12:1) across three levels of MTBF (30kHrs,70kHrs,100kHrs). The computer program addressed panel failures as a Weibull process.[4] That is, the proportion of failures will occur mainly early in the flight and are most easily characterized as infant failures. Using this basic assumption about the array's failure characteristics, an algorithm to approximate this process was developed (Figure 2-3). Figure 2-4 presents a flow chart of the program's operation. Following this, the program iterates through the array failure times as a function of the specified cell and diode combinations. Figure 2-5. gives a matrix of the failures allowed in this simulation. During each iteration, each cell's performance is degraded in accordance with the predicted radiation dosage. Iterations continue until the array output fails to deliver the specified power to the load. The results of the 27 simulation runs performed by the computer are summarized in Figure 2-6. These results indicate that a conventional terrestrial series interconnected panel approach falls short of the 4 year mission life when the array system's characteristic series string MTBF is less than 70 kHrs.

Figure 2-6 shows the respective plots of simulated power output to load for the 30kHr,70kHr and 100kHr MTBF Case. Because no perceptible differences were found, regardless of the underlying Weibull distribution, among the 70kHr or 100kHr family of curves,

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they were averaged. This averaging was performed across all three levels of failure rate and diode combination for each MTBF level (i.e., 9 plots for each MTBF level).

The series string approach, while perfectly acceptable for terrestrial applications, may be improved by alternate approaches if the anticipated failure rates become significant. However, if the assumed operating environment is not excessive, the suggested 9% array oversizing should be sufficient with present terrestrial approaches. In addition, this simulation demonstrated that increasing the number of diodes per set of cells had only a minor influence in improving panel reliability at low MTBF, and at high system MTBF produced no discernible effect. Therefore, the shunting diodes function mainly for shadow protection. Based on in-house cell characterization, this would be on the order of 6 cells for every diode.[5]

2.2.2 Solar Array Tradeoffs

From the conceptual design a set of major solar cell and panel tradeoffs were examined. These dealt with the cells' size, type, cover-sliding method, and the panel substrate approach.

2.2.2.1 Solar Cell Size

In adopting a 5cm x 5cm configuration the first factor to consider are the advantages and disadvantages of this cell size. The major advantages of utilizing this size cell are largely economic:

- The larger cell size allows a greater overall active surface area relative to the whole panel.

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Figure 2-3

Approximation of Weibull Distribution Algorithm Used
In The WinSim Failure Characterization Program
(WINg-SIMulation)
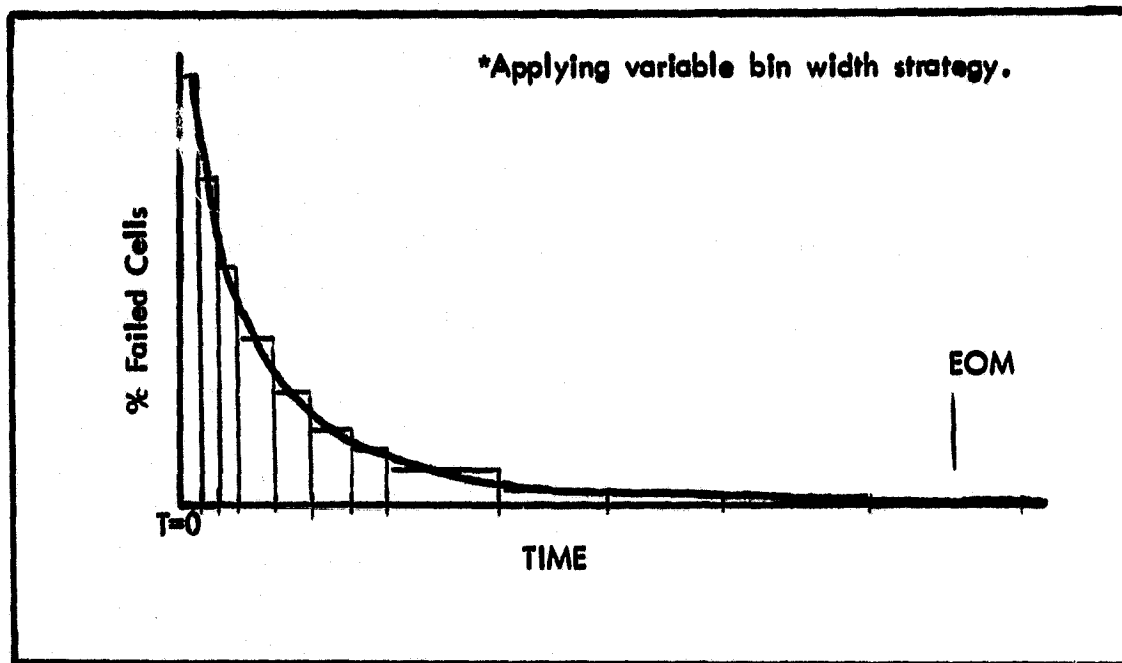
Where:

1. MTBF= 1/(failures expected X Number of Hours in flight)
   (i.e., $1/(1 \times 10^{-9}$ X HRs)

2. Multiply failure density by Number of hours of mission for
   the proportion of failed cells for a given MTBF at a given
   Time T

3. Calculate number of cells affected at a given Time T

4. Randomly distribute failure times of cells derived from
   step 3 over surface of the array wing

Figure 2-4

Computer Simulation Flowchart

```
                          ┌──────────────┐
                          │    START     │
                          └──────┬───────┘
                                 │            ◄─────────────────┐
                        ┌────────┴────────┐                     │
                        │     Input       │                     │
                        │   Simulation    │                     │
                        │   Parameters    │                     │
                        └────────┬────────┘                     │
                                 │                              │
                        ┌────────┴──────────┐                  │
                        │ Compute Distributions of             │
                        │ Failure times for each               │
                        │ component/mode in system             │
                        └────────┬──────────┘                  │
                                 │                              │
                        ┌────────┴──────────┐       YES        ╱╲
                        │     Randomly      │                 ╱  ╲
                        │ Assign failures to Series          ╱  ? ╲  NO
                        │ strings across system             ╱Another╲──► STOP
                        └────────┬──────────┘               ╲ Run  ╱
                                 │                            ╲    ╱
                                ╱╲                             ╲╱
  ┌──────────┐     YES        ╱  ╲
  │ Output   │◄──────────────╱  ? ╲
  │Distribution│             ╲Output╱
  │Parameters│                ╲    ╱
  │ to file  │                 ╲╱
  └────┬─────┘                  │ NO
       │                        │
       │            ┌───────────┴──────────┐
       └───────────►│ Degrade cell performance
                    │ of cells in system for the
                    │ specified interval of time.
                    │ Determine failed compon-
                    │ ents and assign the
                    │ appropriate status codes
                    └───────────┬──────────┘
                                │
                    ┌───────────┴──────────┐
                    │ Compute string Voltage
                    │ and Current for each Sub-
                    │ string system combination
                    │ and place on parallel
                    │ string file structure.
                    └───────────┬──────────┘
                                │
                    ┌───────────┴──────────┐
                    │ Compute array power;panel
                    │ performance statistics and
                    │ power to load values for
                    │ the given interval of flight
                    │ time
                    └───────────┬──────────┘
                                │
                               ╱╲              ┌────────────┐
                              ╱  ╲    NO       │ Output Data│
                             ╱  ? ╲───────────►│    TO      │
                             ╲EOM ╱            │   File     │
                              ╲  ╱             └────────────┘
                               ╲╱
                                │ YES
```

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Figure 2-5

Combinatoric Matrix Used in Winsim

	CELL		
	N	O C	SC*
N	V = P I = P	V = A I = P	V = A I = A
OC	V = P I = P	V = A I = A	V = A I = A
SC	V = A I = P	V = A I = P	V = A I = A

(left axis label: DIODE)

*   These failure modes not considered

P = Present and operating

A = Absent

N = Normal Operation

OC = Open Circuit

SC = Short Circuit

Table 2-6   Failure Characteristics at 30, 70 and 100 kHrs for different Weibull distribution parameters averaged across three levels of cell/diode ratios.

To give a specific example, a panel of 5 cm x 5 cm cells
with 1 mm x 1 mm intercell spacing had 6% more active
area than a panel of 2 cm x 2 cm cells with the same spacing.

● Historically, cell size reduction has been deemed
advantageous because it promoted cell efficiency.
With the improvements in large cell efficiency this
is no longer the case.

● A disadvantage may be realized due to the potential
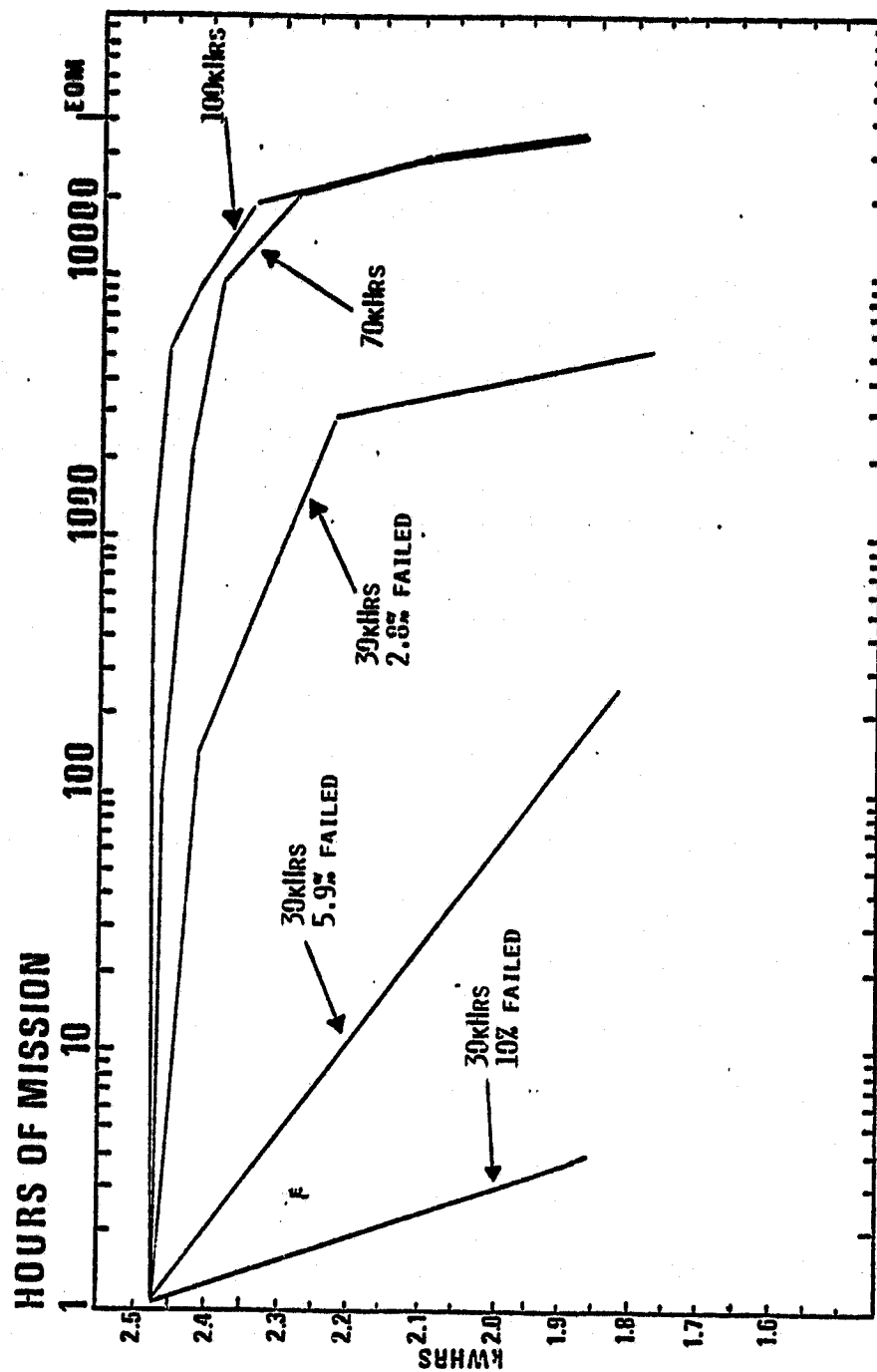damage incurred from thermal cycling in the space
environment using a cell with such large area. How-
ever, using a square configuration tends to decrease
this liability somewhat.

Because of the significant cost savings possible by using
large cells, this type of technology will be considered.

2.2.2.2 Panel Configuration

Several conceptual approaches were considered in selecting
the panel and array frame configuration. At this stage of
the study, various methods used in array fabrication were
considered with respect to the following factors:[6]

o   Weight and size constraints

o   Rigid vs flexible systems

o   Ease of repair

In examining the panels and array wing size, the size of
the array largely dictates the materials approach adopted. In
particular, array size largely determines the choice between

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flexible and rigid designs. Since the rigid vs flexible array approaches were apparently economically equivalent[6], the deciding criteria were shifted to materials availability and ease of fabrication. The rigid honeycomb substrate is more readily available and considerably more convenient to handle and store. Therefore, the rigid array design concept was adopted as the preferred approach. It was also observed that the rigid panel configuration is much simpler to repair or replace in flight than a flexible blanket. Further investigation into the economic tradeoff's between flexible and rigid arrays from a maintainability standpoint may have some merit.

The array frame is envisioned as a hollow structure in which the individual panel modules would be placed. The frame spars themselves could be fabricated using aluminum extrusions having hollow cores to allow the wiring to pass inside (see Figure 2-7). The array frame could be hinged at every 2 sets of panels to allow each wing to be packed within a volume of 1/3 cubic meter (124cm x 247cm x 9cm).

2.2.3 Battery Design, Sizing and Evaluation

Battery sizing indicated a storage requirement of at least 2400 watts for a duration of .62 hours taking into account cabling losses, internal battery parasitic losses and discharge efficiency. This translates into 1485 watt-hours of energy while the spacecraft is in one eclipse. This energy yield is based on a battery discharge efficiency of

1.27 cm

3mm

1.27 cm→
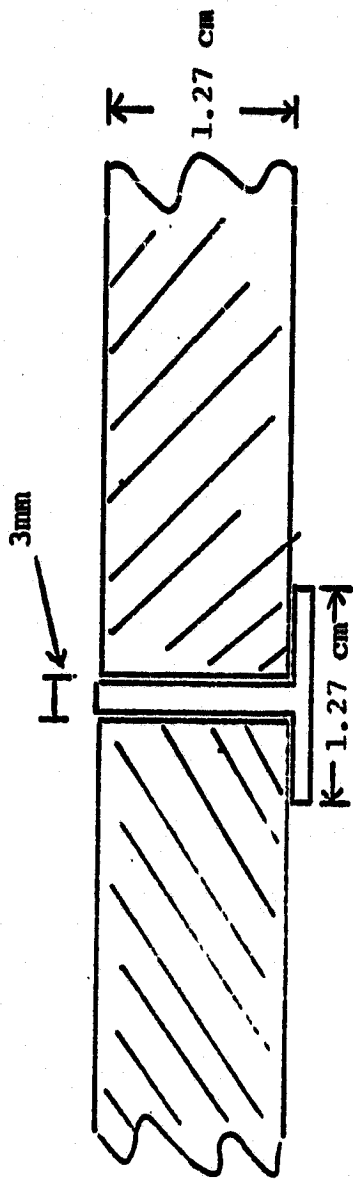
Panel and Honeycomb Sideview

Backview of
Panel

Simple compression
holddown
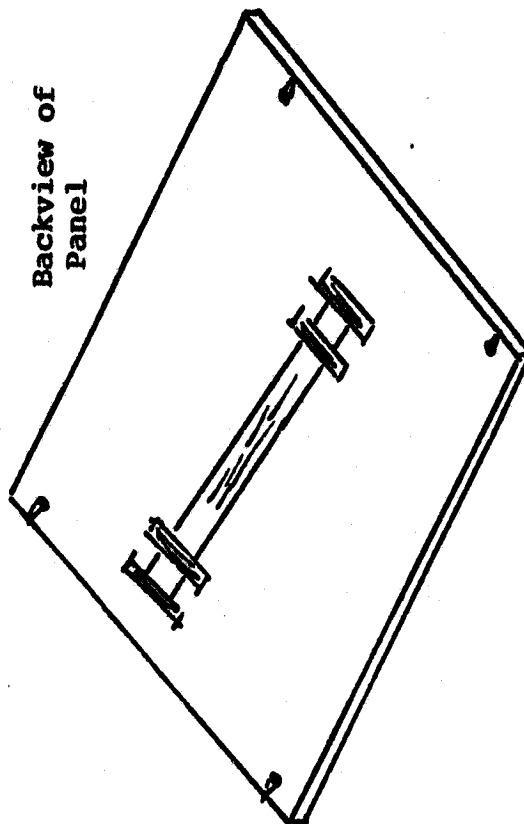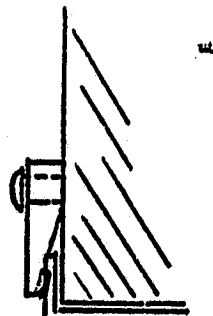
Figure 2-7   Array Panel and Frame Illustration

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83% with an overall charge-discharge efficiency range between 75-80% and ambient battery temperature between 0° (273K) and 15°C (288K) (for maximum cycle life and efficiency).[7,8]

Only lead acid and Ni-Cd batteries were considered, due to their general availability and established operating characteristics. In examining these two battery types, their comparative merits were traded in terms of their applicability for spacecraft energy storage.

Lead acid batteries are more widely used for terrestrial applications than any other kind. This is largely because they are derived from a mature technology, the materials are relatively inexpensive, and they have been in mass production the longest. The most likely lead-acid battery candidate for space use would be the lead-calcium type with gelled electrolyte. This battery exhibits improved cycle life and depth of discharge as high as 80%. However, even with such technical advances, lead acid batteries are not typically operated in the same modes as would be required for a spacecraft energy system.

On the other hand, Ni-Cd batteries have been proven reliable for long-term energy storage in space. Ni-Cd batteries have been used in both low and geostationary orbits, withstanding in excess of 40,000 discharges before failure[8].

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Typical traditional space approach to using Ni Cd battery systems generally means charging to nameplate capacity. Imposing this requirement, in addition to using a shallow depth of discharge, has become accepted practice in obtaining a long cycle life. However, if charge level is reduced to 85 or 90% of nameplate capacity, it has been suggested that other advantages such as reduced stress and lengthened cycle life are possible. This is because as the cell nears full charge, parasitic side reactions begin to occur as well as outgassing and heat evolution. At high charge rates, typical of Low Earth Orbital missions, these parasitic reactions can be detrimental to battery life. Ni Cd cells are traditionally positive limited so that when the positive (nickel oxide/hydroxide) electrode is fully charged, oxygen tends to evolve. If the oxygen is allowed to build up, the cell will eventually rupture. This is part of the rationale behind space Ni Cd batteries having strong stainless steel casings. This oxygen eventually diffuses to the anode and becomes re-oxidized with the Cadmium, further accounting for electrical losses. To permit diffusion, space cells are usually starved of electrolyte. As the cell ages, more and more electrolyte is irretrievably lost into small cracks and pores, further drying the cell. This eventually leads to higher internal resistance and greater difficulty recharging.

Another problem with charging to nameplate capacity in Ni Cd cells is the overloading of active material into the electrodes. This requires that the cells have a minimum depth of discharge in turn reducing the watt-hour output. The shallow discharge cycle eventually yields a "memory effect" which needs periodic "reconditioning" to return the battery to full capacity.

It is suggested that replacing space Ni Cd cells with avionic Ni Cd cells will lead to a cost saving. A typical avionic Ni Cd cell has an energy density and cycle efficiency comparable to that observed in space-qualified cells.

To effectively utilize an avionic Ni Cd battery for space, use of the following design features are recommended:

- Limit peak charge to 85% of nameplate capacity to minimize the evolution of oxygen and pressure build up.
- Optimize charge strategy to maximize performance of battery.
- Employ temperature and voltage sizing to protect batteries against overcharging.
- Provide capability for reconditioning.
- Mount aircraft cells in a container with individual slots for each cell, with mica sheet surrounding each cell for electrical isolation.

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- Replace venting caps with resealing pressure caps
  and attach cabling and seal cells into each slot
  to the top of the pressure relief valve with an
  outgassed silicone or other rubber compound.
- Specify a valve pressure of between 100 and 300 psi
  and verify that the resealing valves will be vacuum
  tolerant (see Figure 2-8 for an illustration).
- Use an absorbent material to eliminate the loose
  electrolyte in the battery container.

If the avionic battery approach were adopted, small
sealed battery modules could be distributed around the
perimeter of the craft. By having a quick disconnect electrical coupling with a tongue-in-groove battery base (or sides)
mounting, in flight repairs could be expedited using a replace-and-discard approach.

A major concern, possibly more important than battery
performance, is the design/fabrication scheme and test plan
that would insure man-rating of these units.

2.2.4 Power Regulation Design

Terrestrial applications dictate the use of simple
approaches to power regulation, ostensibly to improve reliability. Such approaches generally require increased
array or battery size to compensate for losses due to inefficient energy regulation. Two simple power regulation
approaches were considered for controlling battery charging

Pressure valve replacement
for vent cap.

Wire

Ni Cd

Absorbant wicking material

Outgassed/Cured Plastic
Polymer poured over cell.

Ni Cd
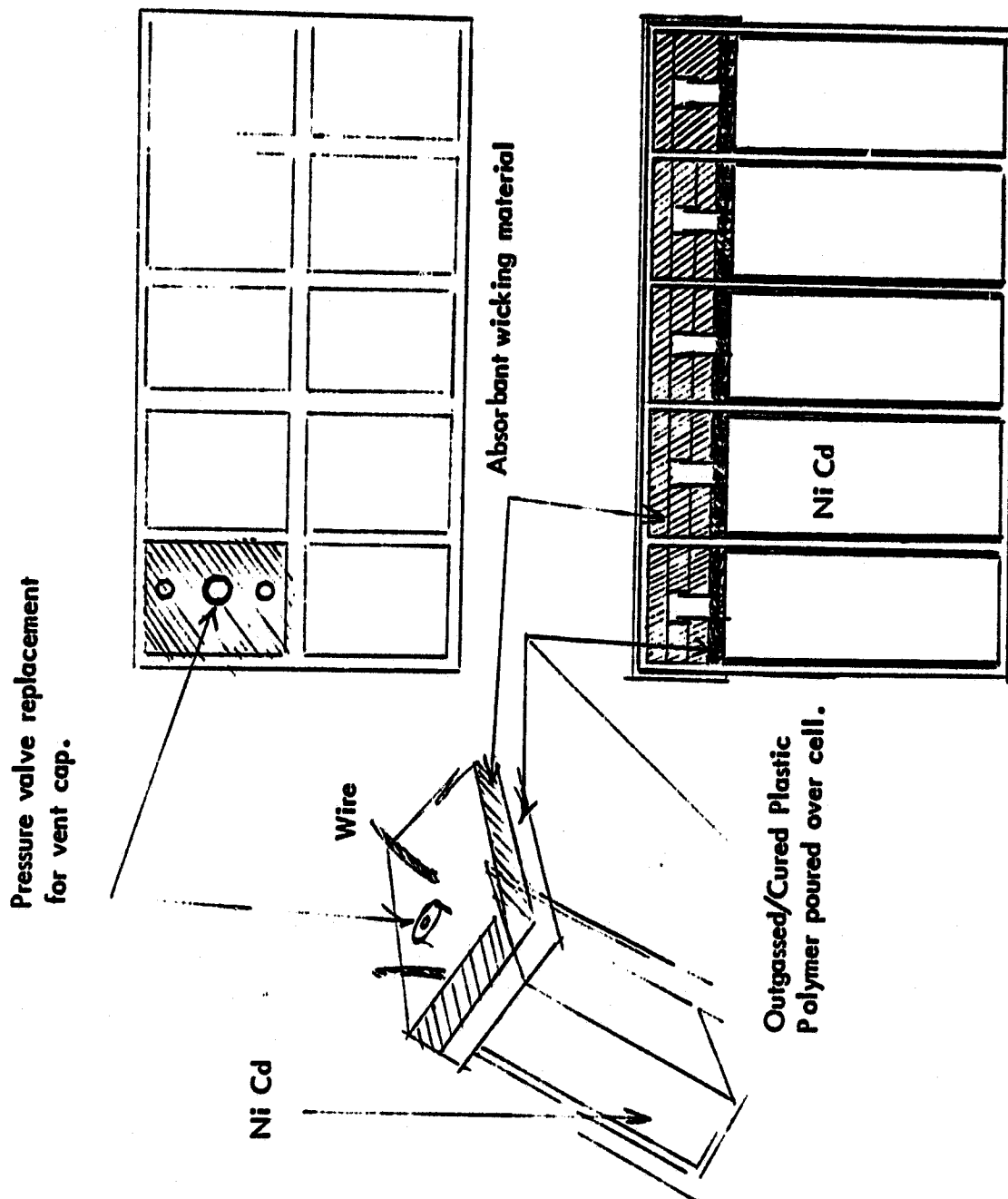
Figure 2-8   Avionic Battery Containment Approach

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and delivery of power to the load:

- Array Detracking - As charge to the battery reaches maximum charge, the array is turned "off axis" from the sun. This technique is used in some concentrator photovoltaic systems. Similarly, allowing the tracking system to lag behind the sun's position produces the same effect.

- Panel Switching - Segments of the array are switched out of the system as the charge to the battery reaches maximum. A set of electrically isolated array subsections are connected in parallel to the main bus. By disconnecting subsections, the power to the load and charge rate to the batteries can be controlled.

These two approaches were rejected because both have potential problems. Array detracking would produce a large amount of dissipated energy in controlling battery charge, while switching array segments would cause large transients which would reduce battery life.

The final tradeoff study between the type of power/ charge regulation resulted in a choice between either shunt or switching regulation. With shunt regulation, the excess array output is dissipated via variable-resistance elements

such as a set of power transistors. This will radiate con-
siderable heat when used on a system as large as the one con-
sidered for this study. This radiation will always have to
be directed to the eclipse side of the spacecraft to reject
the heat. Shunt regulation generally is characterized by
the following:

- Simple Circuitry - A simple D.C. voltage feedback
  circuit is used to control the variable resistance
  element.

- Long Mean-Time Between Failure (MTBF) - In com-
  mercial applications and normal operating conditions
  shunt regulators can have an MTBF upwards of 3 times
  that of switching regulators.

- Quiet Operation - There is very little electrical
  noise produced by the circuit.

Pulse width modulating (PWM) type switching regulators
operate by chopping the D.C. available from the array into a
square wave of variable duty cycle. By using such a control
scheme, the array can be operated on a portion of the current-
voltage performance curve that provides a power output that
matches the system demand. The following items are characteristic
of PWM regulators:

- Excess array output is not utilized and thus is
  dissipated over the array surface. This added
  thermal load is extremely small when distributed
  over the array.

- The array can be operated at peak power conditions when the demand is equal to or greater than maximum array output, thus optimizing the array's output for various load conditions.

- Even with increased functional and component complexity the total subsystem size and mass is considerably reduced from that of a shunt regulator because of the increased efficiency and reduced thermal dissipation problems.

The PWM regulator was considered to be the superior design, based upon a comparison of size, weight and performance capabilities.

2.2.5 Battery Charge Control

The PWM regulator approach offers an opportunity for expanded control of subsystem functions. A microprocessor based controller offers advantages not only for charge control, but also as a means of minimizing performance losses due to failed battery cells or Ni Cd battery memory effects. On board firmware (i.e. on board Read Only Memory (ROM) programs) could be used to; a) control and regulate charge of battery submodules based on age and performance, b) control and assign selected modules for reconditioning and c) serve as an active mechanism to maintain battery life/reliability. This approach was adopted because microprocessor components constitute a relatively economical approach to controlling complex operations

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at a very low energy, weight and size expenditure.

Inputs needed to control the PWM regulator's pulse generator would be the following:

a) Load power demand

b) Storage energy level

c) Storage temperature

d) Array peak power

Items a) through c) are straightforward control problems that could be monitored by the charge controller using analogue/digital conversion. In the case of item d), which is more complex, the control circuitry would continuously vary the duty cycle and monitor the power output. As the duty cycle decreases, the power output falls until the peak power point is passed. Immediately the process is reversed and the duty cycle is continuously modulated around the peak power point. This is commonly referred to as peak power tracking, used in all new large terrestrial photovoltaic applications.

2.2.6 Slip Rings and Array Drive Assembly

Several corporations were consulted for assistance in slip ring design (Appendix A). There are three major concerns:

● Vacuum welding of the contacts to the rings

● Vacuum tolerant lubrication

● Voltage drop across the slip rings

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Several alternatives were suggested for a commercial system design which offered cost savings. One such approach was the use of radar type slip rings. However, little information was obtained that would justify use of this approach over that of an already proven space qualified approach.

Generally slip rings are of two basic configurations; a) cylindrical and b) disk type. Configuration is dependent upon specific application. For this system it was concluded that materials cost would be reduced if the disks were milled from copper stock with gold or silver plating. The contacts or brushes would be fabricated of a composite material with lubrication an integral part of the brush. This is common practice for space use; no economical improvements are evident.

It was concluded that using a non-proven approach in order to reduce cost would not be worth the risk. There is little or no demand for such technology in terrestrial-commercial applications making it difficult to prescribe novel alternates allowing sizeable cost reductions.

The approach to design of the slip ring assembly is to identify the major cost drivers and make necessary modifications to allow rapid inflight repairs, such as:

- Providing faceplates to the ring and brush assembly.
- Engineering the brushes so that they may be easily removed and replaced as a modular unit.

- Providing a system wherein the whole slip ring assembly -- drives, rings and housings -- can be easily replaced.

2.2.7 Array Drive Approach

Several alternatives to array drives were considered:

- Direct drive - The motors and array drive shaft are conceived of as a single integral unit.
- Stepping motors - Systems analogous to disk drive systems found in other applications.
- Harmonic drives.
- D.C. torque motors (brushless type) -- with gear reduction.

It was determined that a D.C. brushless torque motor with gear reduction was the simplest approach. By externally mounting the motor in line with the axial plane of the spacecraft, a failed motor could be easily disconnected and replaced in flight. Motors and drive assembly would be configured and supplied by qualified vendors with space experience.

2.2.8 Deployment

Two general approaches to deployment are generally accepted:[6]

- The pulley-cable and spring actuated system
- Extensible beams or coiled beams

Based upon this system's requirement of having a both
deployable and retractable array, the approach was to use
an extensible beam and lazy tong system. Figure 2-9 gives
a conceptual illustration of the lazy tong/coiled beam
approach.

In this design the coiled beams would be housed at the
base of the array. A D.C. brushless gear reduction motor
would be located in the center, with a coiled beam
situated at each end of the central axis. The outermost
end of the lazy tong would be rigidly fastened to the outermost
spar of the array frame. The lazy tong would be extended
with actuation of the coiled beam. All segments of the
lazy tong hinge points would have guides through which the
coiled beam would traverse.

Applying the combination of these two proven deploy-
ment concepts provides a fairly simple approach to remotely
actuated deployment and retraction. This was considered
in the design because the arrays could be remotely retracted
prior to storage inside the shuttle bay. This would allow
inflight repair or be returned to earth for repairs.

The major constraints on using this system are the size
and weight limitations. However, the approaches used here
have had prior flight testing and are considered favored
approaches.[6] Comparable terrestrial systems having the same
limiting requirements do not exist. Therefore, because of

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Figure 2-9   Deployment Approach

Solar Array

Extendable
Boom Housing

Coiled Beam.

Lazy Tong

Solar Array

Deployment
Motor

Coiled beam housing

Coiled be am

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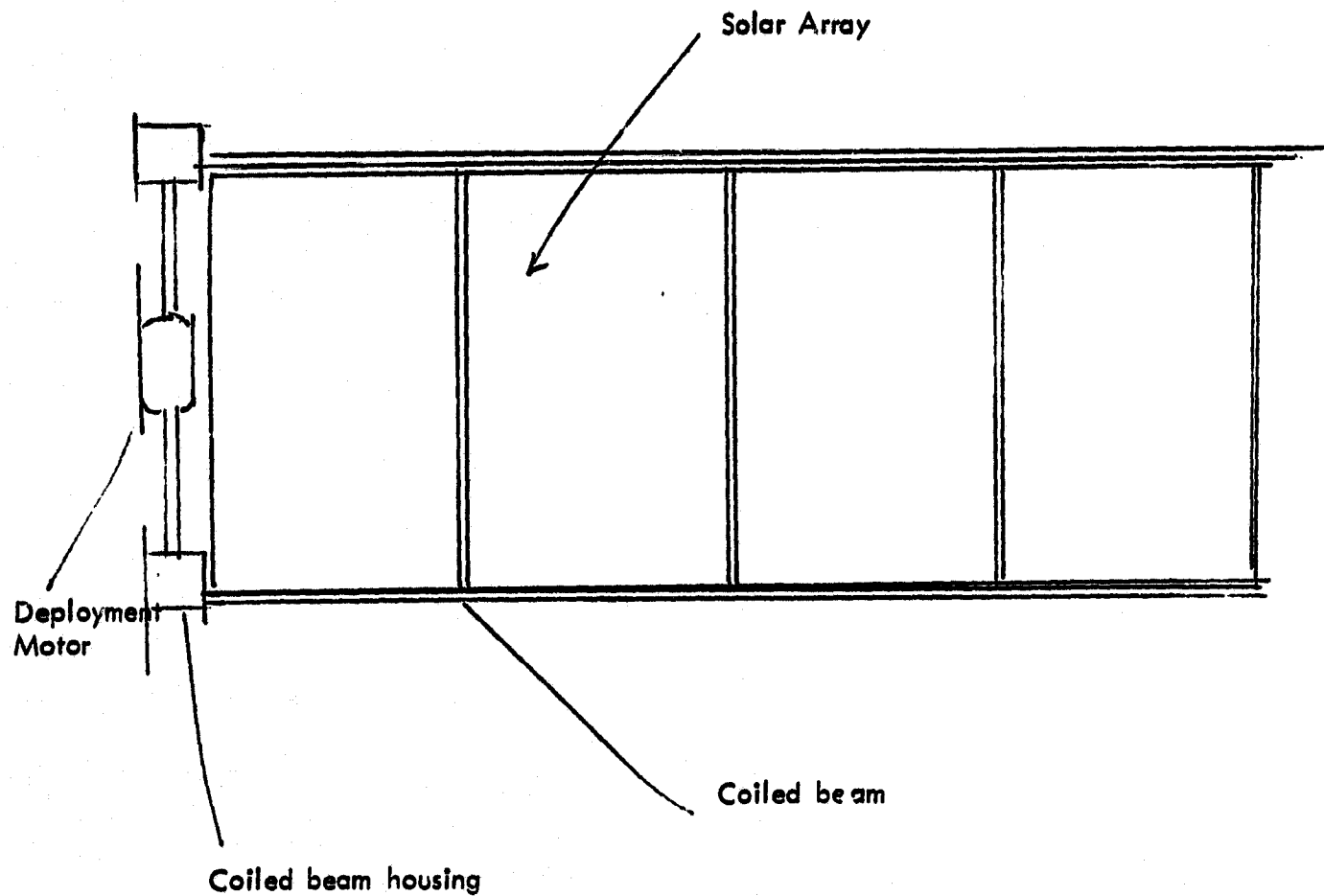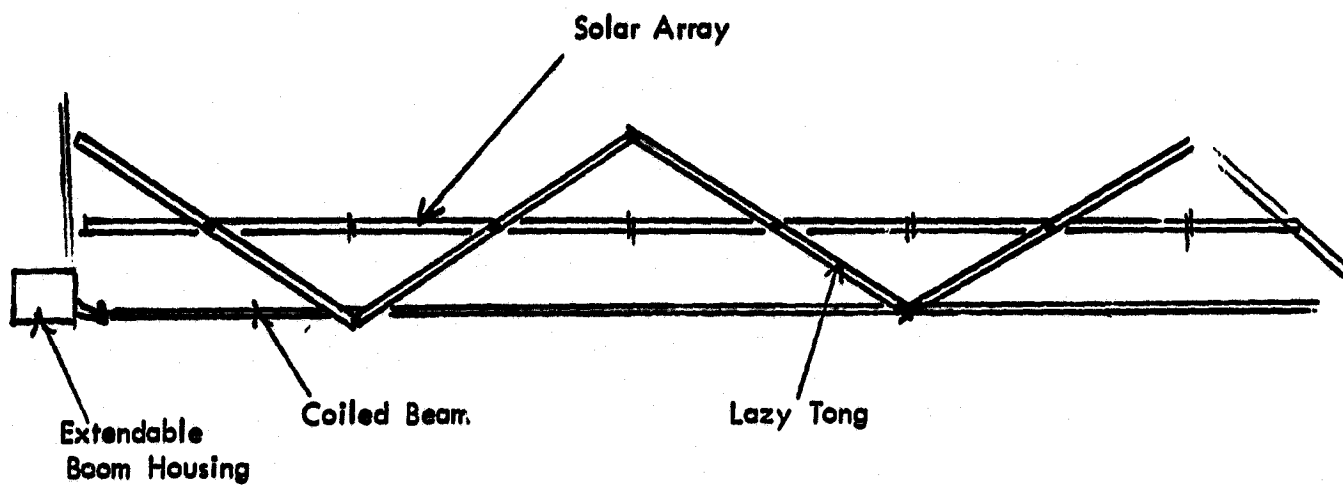
the lack of comparable analogous commercial use, it is felt, as with the slip ring assembly, that the typical space approach would prove the best.

3.0 An Approach to Design, Documentation, Fabrication and R&QA (Task II)

3.1 Project Organization

A typical project organization for generating a commercial space power system is presented in Figure 3-1. As this project is designed, depending on organization and complexity of the job, many of the functional blocks in Figure 3-1 can be combined and the total project may consist of a relatively small group of engineers. As presented, three major managerial functions are employed:

- Program Manager
- Configuration Control Manager
- Quality Assurance Manager

The program manager and quality assurance manager would both report directly to corporate management. The configuration control manager would not usually report directly to management except on an informal basis to reinstitute needed realignment of the quality assurance and program managers. Otherwise, the configuration control manager would serve as mediator of demands put forward by the Q.A., design and production groups.

3.2 R & D Process Flow

The first step in proceeding with the project, subsequent to defining the organization and reporting structure, is to translate the power system specifications into workable subsystem specifications. It is of utmost importance that a

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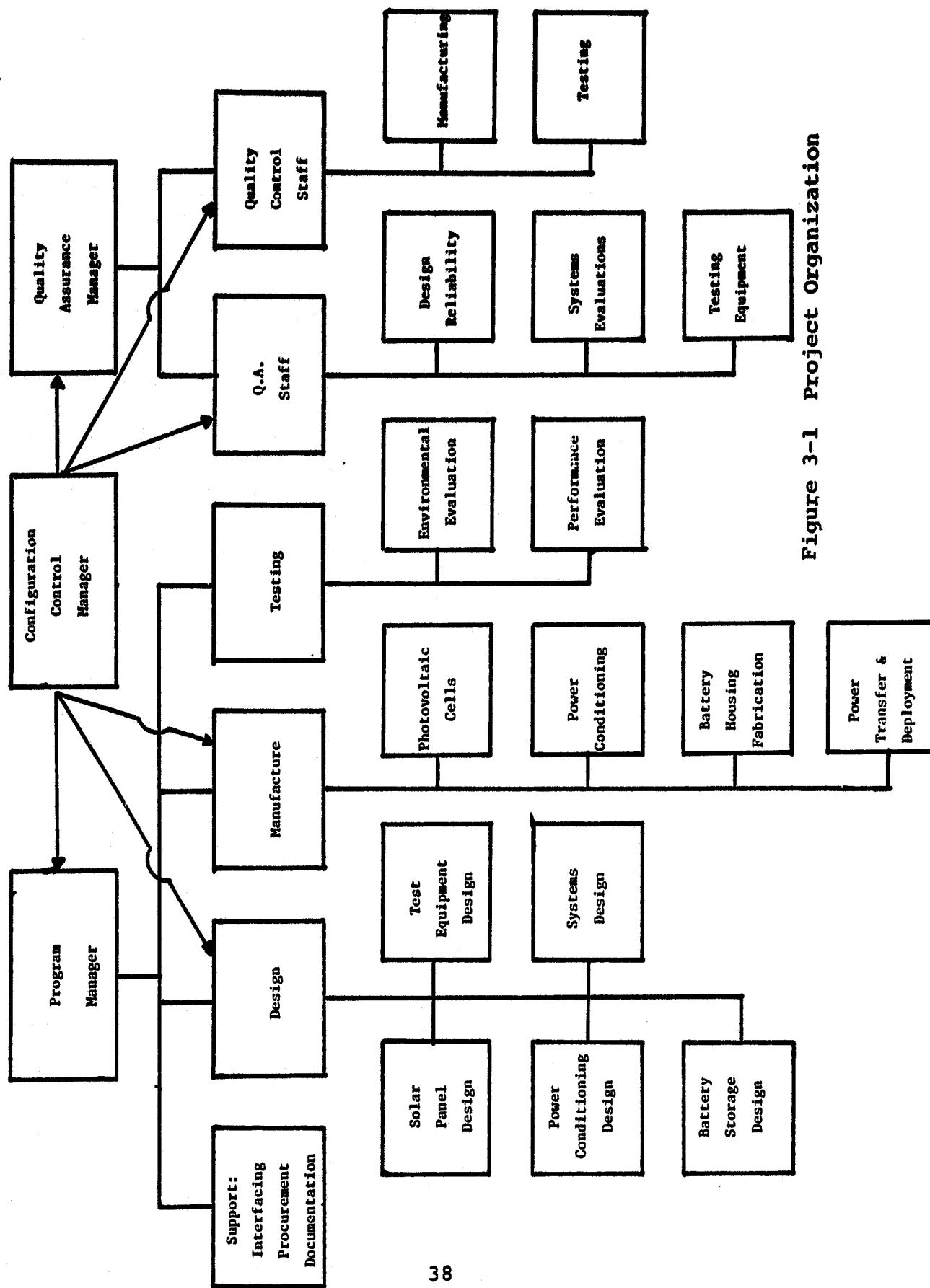
Figure 3-1   Project Organization

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consistent set of functional specifications be prepared for the system and subsystems. This will maintain uniformity and insure an acceptable approach to meeting the requirements of the spacecraft.

Three major levels of design are employed which would function iteratively to successively achieve a final detailed system design. The first level is a "first pass process" of dispersing the translated specification of each subsystem to all team members. Sketches are then initiated and preliminary calculations made. Literature searches follow so as to discriminate between one approach and another. At this conceptual level all major tradeoff studies would be identified. Some of the tradeoffs are as follows:

- Solar Array Area vs Cost -- The cost/unit panel tends to decline as array total area increases because the production runs for a particular cell and system will experience economy of scale.

- Power Conditioning Efficiency vs Cost -- An increase in the efficiency of power conditioning reduces the cost for the entire system.

- Battery Sizing vs Cost -- Reduction in battery size and increase in depth of discharge will reduce the entire system cost.

- Solar Cell Performance vs Cost -- The entire system cost is reduced as a function of improved cell performance, which includes radiation resistance.

- Weight vs Cost -- Increase in system weight causes increase in the cost to place the system in orbit.

- Redundancy vs Lifetime and Cost -- Increased sub-system redundancy will increase the probable life-time of the entire system. However, this factor must be traded against the projected cost of main-taining the system. The issues of reliability, redundancy, environment, and system limitations of the spacecraft would be examined from the initiation of the first design level. This would be done by the project manager with interactive support from the design, manufacturing, test and quality assurance teams.

Component availability would be reviewed in relation to cost and factored into the process of comparing and contrasting the alternative approches. The prime system candidates are reviewed and then passed on for further development.

The second phase of design, in form, is also iterative in nature. During this design phase, analysis of the various subsystems and their interfacing becomes more detailed. The major conceptual and evaluative tradeoffs concerning the operation will be performed. Assuming the subsystem achieves adequate description of the functional needs and documentation, initial detailed design specifications are then developed

by the various subsystem teams. This effort is primarily
led by the systems groups, which insures that the overall
focus of the project is maintained and the performance
criteria are met. The different subsystems design engineers
generate their initial set of detailed drawings and analyses
of performance and operating characteristics. The various
subsystems will be required to show their compatibility with
the whole system in the second phase. The detailed drawings
are then transmitted to the manufacturing and test groups.
Tooling considerations and make/buy decisions are initiated
at this time. Problems and progress from the different
teams are reflected back to the project manager to assure
that good tradeoffs are being employed, followed by
an acceptance review of the system.

The final design level encompasses the process of
prototype evaluation and operation. For reasons of reducing
development cost, the prototype and flight model will be one
and the same. Subsystems which constitute major building
blocks of the power system would be constructed and tested
to evaluate design assumptions. These test results will
verify the approach and document the changes needed for the
final detailed designs. At the conclusion of this design
and development step, the systems' designs will be completed.

3.3 Method of Assessment

The method used to determine tasks and manpower for this effort was based on selected in-house personnel and outside expert personnel. Within Solarex, selected managers, electrical and mechanical engineers, and scientists with the necessary skills were interviewed for definition and appraisal of tasks, skill levels, and manpower required. Individuals were paired with a particular subsystem and given the information presented earlier in the conceptual design. Each individual was asked to do the following:

- Identify the important technical and manpower requirements with regard to developing that particular subsystem.

- Estimate the professional and technical requirements of the tasks they identified.

- Based upon prior comparable tasks with which they had been involved, estimate the time required for each task. From these interviews task/manpower descriptions were generated. For this study, four general skill classification's were utilized:

  - Administrative Professional (AP) -- This defines a management level individual empowered to issue policy relevant to a task, assign team members to specific duties and commit

resources toward completion of task. Additionally, individuals at this level have project and budgetary responsibility. Wage scale estimate is set at $16.82/Hr.

- Professional Technical (PT) -- This defines a labor category of a broad group of professionals ranging from engineering to scientific. These individuals are not empowered to commit large budgetary sums or delegate a large portion of Company resource as is the case with the Administrative Professional. Wage scale estimate is set at $9.61/Hr. for purposes of the study.

- Technician (T) -- Skilled laborer in electrical and electronic device repair, drafting and design and other related areas. Wage scale estimate is set at $7.69/Hr.

- Secretarial/Support (S) -- Semi-skilled or unskilled labor. Wage scale estimate is set at $4.90/Hr.

Task, manpower and cost estimates must be viewed relative to the degree of direct experience the individuals interviewed had in configuring similar commercial and/or space subsystems. There is the possibility that the commercial approach is modified somewhat by personnel who have acquired approaches

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and attitudes from previous aerospace experience.

Estimates of manhours, and the cost of hardware and
materials were obtained either from vendors or by collect-
ing pricing information. R&QA costs and manpower estimates
were based on in-house solar cell price lists and labor
reports and by task/manpower costing exercises.

3.4 Power System Design

This subsection will examine the major design functions
that comprise the power system.

3.4.1 Solar Cells

Eight major process steps in the design of a Solarex
Solar Cell are as follows:

1. Light Intensity Determination--The light intensity
determination is formalized and the environmental conditions,
in terms of available light energy, are evaluated. An initial
estimate of cell output is made to determine whether the cell
is utilized in an AMO, AM1, rotating satellite or under
concentration. This estimation process gives the cell designer
an initial approximation of the energy incident on the cell
per unit area.

2. Interconnection Determination--The interconnection
method -- single, double, triple or continuous contact
pads -- is considered as part of the cell's integration
into the overall array design. The cell designer will

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interact with the array designers to arrive at the inter-
connect system to be utilized. These factors must be
determined exactly for the cell designer to derive the
cell system design. This design process only partially
relates to performance.

3. Power Requirement Determination--Array power
output is determined from the conceptual design, vendor
supplied specifications, the effective area the designer
has to operate within, array voltage and current, estimated
light intensity and temperature. From this analysis the
recommended number of cells per series string and expected
output is calculated.

4. Surface Preparation -- This design step is required
to identify whether or not additional output is necessary.
Additional steps in the design would be implemented if higher
performance and radiation resistance is required, cell thick-
ness and surface formation are also evaluated. However, as
performance and design constraints escalate, more exotic
surface preparations (such as using an ultrathin textured
cell) evolve. These processing additions, while not sub-
stantially costly design items, do create tremendous in-
creases in labor and processing costs. These design features
are not looked upon as a cost saving unless it is determined by
tradeoff analysis that their added cost is justified by the uniqueness

of their application and improved efficiency.

5. **Base Resistivity Analysis**--Based upon the power, radiation resistance, voltage, and current requirements, selection of the silicon is made. If high radiation resistance is called for, the 10 ohm-cm silicon would be used. This material typically gives lower voltage output, and concommitantly would realize lower production yield to achieve the specified performance criteria. Moving to a 2 ohm-cm base resistivity immediately elevates voltage and improves yield. A tradeoff must be made to examine whether or not the impact of radiation on performance over time is sufficient to limit yield by using a higher resistivity base material.

6. **Front/Back Surface Contact**--The cell's operating conditions and the front and back contact materials generate the materials configuration. Typically, a Ti-Pd-Ag metalization scheme is recommended, however, if temperature extremes are suspected, tantalum maybe exchanged for titanium. Two methods are generally available in front grid preparation for high efficiency cells:

- shadow masking
- photolithography

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Characteristically, from a production standpoint, photo-
lithography is the favored approach for these reasons:

- It provides a wider range of pattern and design
  flexibility.
- It is more amenable to high production.
- It allows use of a broader range of metals.

Similarly, electroplating is favored over evaporation
because of the producibility, throughput rate and cost.

7. Front Grid Pattern Analysis--Based on the cell's
shape, contact pad, and metallization requirements, a geo-
metrical analysis is performed. This determines what
shape the grid lines should be to achieve maximum effi-
ciency. Items to be considered are:

- Which design gives best performance
- The impact of the design on production yield
- Reliability of design

The design reliability feature is important for two
reasons:

(1) By offering a redundant path the maximum power
     loss, if a contact pad falls off, is usually
     about 5%. Greater performance is assured if a
     micrometeorite impacts or cracks form in the cell.

(2) The redundancy in the grid pattern also is an
     added production yield asset because a greater
     proportion of the cells will have good performance

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even with minor finger losses on the grid pattern. This inherent design improvement also limits the amount of Q.A. required.

Usually, two or three candidate designs are developed. These design candidates are parameterized and then submitted to a series of topographical analysis programs which define the approaches and modifications that will optimize the candidate design. These resultant outputs are then evaluated in terms of each system's producibil. /, reliability and added process technology considerations. From this the final design is selected.

8. Cell Efficiency Analysis--After an optimized design is obtained, a theoretical analysis is conducted considering all of the prior design process steps. All of the relevant design parameters which were determined are then modeled to estimate the expected cell performance characeristics.

A.   determination will be made of the following parameters:

- P_{max}=Maximum power output
- V_{oc}=Open Circuit voltage
- V_{max}=Voltage at maximum power point
- I_{sc}=Short circuit current
- I_{max}=Current at maximum power point

$P_{loss_{1...n}}$=A set of power loss variables in the operational system.

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-- grid shadowing losses

-- sheet resistance of silicon

-- grid resistance losses

-- bulk resistance losses

This analysis serves as a model for sizing of the array, a functional criterion to compare with R & D pilot production and subsequent mass production.

3.4.2 Solar Panel

Typically a Solarex terrestrial panel does not employ the same design features as a space type array. Such differences are:

- Heavy frames and glass coverings for wind loading and vandalism.

- No design consideration for radiation degradation

- Less packing density of solar cells on panel, i.e., cell packing density is not crucial for terrestrial panels.

- Liberal use of Silicone/Acrylic materials with only some vacuum pumping to draw off air bubbles during the cell-to-substrate laydown procedure.

- Only in production of a Solarex concentrator receiver is glassing of the cell with microsheet coverslides performed.

- Adherence to thermal cycling : In both space and terrestrial approaches thermal stress relief is required, but terrestrial panel requirements are not as stringent.

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For this subsection the task manpower analysis was based on
5 major tasks deemed relevant to panel design for a space
panel.

1. Coverslide Design--This design would: (a) examine
the type of cover glass required, (b) degree of required
overlap (i.e., from proton radiation damage), (c) the effect
of nonuniform coverslides on cell damage, (d) the proper
microsheet thickness, and (e) seek bids from vendors for
this material. The following are tradeoffs specific to
this design step:

- The cost of vendor cutting versus in-house dicing
  of the microsheet.
- Optical matching of the cell coverglass and addi-
  tional glass preparations.
- The cost of cutting back on materials specification
  and design requirements relative to power losses
  from a simulated degradation analysis.

2. Adhesive Interface Analysis and Optimization--
Perform an analysis and determination of silicone adhesive
thickness. A problem may arise from incompatible thermal
coefficients involved in the coverslide-adhesive-cell
interface when considering a larger cell size. However,
preliminary evaluation suggests little likelihood of damage
using the square symmetry of the 5cm x 5cm configuration.

Only panel prototypes would be constructed and thermal
cycled. Thermal shock test would be used to determine the
validity of the design approach and materials selection. The

designer must also examine the risk associated with radiation testing relative to estimation of degradation. This would be dependent upon in-house archived information about comparable systems (i.e., Solarex cells) performance. Because such testing would involve considerable cost, radiation testing might be eliminated altogether.

3. Interconnect and Wiring--The major elements of this design task consists of selection and analysis of the approach to interconnecting the solar cells and panels. This involves several factors:

(a) Examination and analysis of interconnect materials;

(b) Evaluation of prior systems and approaches;

(c) Examination of the resistance to thermal stress of the materials used;

(d) Computing and specifying how and where the interconnect thermal stress relief is based on calculations of the estimated distances the cell will creep. Comparable work has been performed in designing standard terrestrial cells and interconnects for Solarex concentrator receivers. These undergo fairly large ranges of thermal stress at rapid intervals. As the conceptual design points out, a preliminary selection of fine grid silver mesh soldered to the bus pads was made. However, cost reducing approaches using aluminum mesh are also possible.

4. Substrate Frame Design--The substrate system for constructing a panel involves examination of effective methods of cell-to-panel lay-down. This design step would select adhesives and substrate laminations to provide:

- Simple economic lay down procedure
- Compatibility with thermal cycling
- Good electrical isolation of the cells from the substrate honeycomb back.
- Capability of withstanding the differential thermal stress arising from the back bus contact and the adhesive interface.
- Analysis and testing of thermal conduction and stress of the cell-to-panel system.

5. Panel Electrical Design--Assuming a simple series string approach to the panel design, the analysis and design of the type, number and positioning of shunt diodes and blocking diodes in the panel would be performed. This entails:

- Evaluation of the Solarex 5cm x 5 cm cell's reverse bias characteristics, shadow analysis and failure analysis. This analysis would be performed in conjunction with the Q.A. personnel in order to derive what the major failure modes would be under actual operating conditions.
- Placement of the diode, diode placement costs, and estimation of fabrication difficulty will figure

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strongly into selecting an approach.

- The array panel and wing interconnection design requires an examination of connect and disconnect methods of individual panels in the array frame. Working tolerances, design of wiring paths, calculations, type selection, length and weight of the panel wiring system are all to be determined.

3.4.3 Battery Subsystem

In some respects, the battery system can be viewed as the most problematic subsystem to deal with. Eight major steps have been identified for the cost/manpower analysis.

It is tentatively assumed that aircraft Ni Cd cells will be used in the costing and design exercise. Whether or not use of such an approach is truly viable is perhaps beyond the scope of this study. However, what is given in this subsection is an alternative based on the considerations and assessments presented in the conceptual design section.

The major design steps for the battery are as follows:

1. Preliminary Design Study--Inputs from the array group and the power regulation groups would be obtained by the engineer. The characteristic voltage transients and battery charge characteristics are the first factors to be investigated. This process would entail developing the optimal charging profile, peak charge and charge rate configuration. Specific design trades relevant to the

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charge-discharge cycle would have to be addressed when
examining the application of an aircraft battery for space,
such as:

- Determine charge strategy as a function of--
    1. Peak charge
    2. Rate of charge
- Endothermic and exothermic processes.
- Investigate the relationship between battery
  energy capacity and typical aircraft operation.

2. Battery Selection--Performance and engineering design
data from candidate vendors would be obtained concomitant
with the first step. Using these data a selection of the
vendor would be made.

After battery selection is made, the process of deriving
an acceptance testing procedure would be initiated. A
method is required for characterizing cells with respect to
their operating environment. An attempt to reduce cost
of testing and analysis of summarized in the steps
below:

- Thermal soak the cells to the maximum predicted
  temperature observed in the spacecraft. The
  duration will be long enough to insure that the
  cell is stabilized at that temperature (i.e., up
  to 24 hours). The batteries will be charged to 95%
  of nameplate capacity based on data provided by
  the vendor and measurements made in house.

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- Discharge cell at one-hour rate, measure the battery's temperature, voltage and polarity continuously and document the data.

- Repeat this process for the lowest predicted spacecraft temperature.

- Establish an a priori voltage, temperature cut-off acceptance criteria.

3. Battery Enclosure Definition--The battery enclosure will be evaluated relative to the pressure, thermal and electrical isolation constraints that are imposed on the design. Some possible alternative containment materials are:

- Carbon and resin fiber matrix
- Stainless steel
- Engineering plastic

The two central requirements associated with applying these different materials and containment system design are light weight and minimized outgassing. The issue of outgassing is linked to both charge-discharge strategy and design life (or reliability) of the anticipated battery system.

The plastic or carbon resin container is favored over stainless steel because molds can be designed and produced much more easily. The method of holding the individual cells and providing pressure relief and wicking material to absorb outgassed vapors from the cells is another design consideration in the containment definition process.

4. Battery Load Characterization--The load management strategy will be generated using information from the acceptance testing procedure. Factors such as the array tracking, demand profile and load profiles of the other systems would be characterized. This task will be performed to examine whether or not the energy storage system design will operate adequately under the types of load conditions it is presented with.

5. Terminal Voltage Analysis--This design step would examine a variety of component factors in the battery system operation. The terminal voltage analysis would take into account such factors as the battery system state of charge, battery subunit degradation over time, temperature and load. These performance factors would be analyzed in order to develop a battery circuit design. The number of subunits and diode placements for cross ties in the system would be examined in order to account for nonuniform decrements in performance associated with subunit internal impedance, self-discharge and memory effect of the battery system. This design approach would be traded against the cost of repair to determine the level of self-contained circuit protection and added hardware necessary to minimize failure.

6. Load Variance Analysis--Information obtained from battery load characterization and terminal voltage are then used to assess the effects of large current surges, peak and average load demand during both charging and discharge

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cycles in orbit. This information will then be used in the development of the charge controller's onboard control programming.

7. Weak Battery Strategy--A weak battery strategy is developed in order to determine the extent of; a) parallel cross-ties in the battery system, b) Blocking diodes, c) switch gear, and d) number of backup subunits needed to minimize failures. These methods of improving reliability are traded against cost and performance requirements in order to arrive at a final battery circuit design.

3.4.4 Battery Charge Controller

The battery charge controller will utilize a digital microprocessor. The following general design steps are identified:

1. Conceptual Design Optimization and Verification-- The charge controller would be divided into functional subunits before the design effort begins. Literature reviews on design approaches and component availability are then made. Candidate components are then evaluated for their capability, MTBF, and unit cost. The more sophisticated microprocessor systems usually are more self-contained, requiring fewer added circuits and components.

The features of processor speed and programability also need to be evaluated. Ease of programability is one of the most important cost factors to be considered in such

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a system. The last design factor to be considered in the design is the power requirements and the space availability.

Once a general design is established and a methodology defined, the system is then translated into a detailed set of drawings and specifications. A design review would be held to assure the design approach would perform to specification. A review failure would constitute another iteration until completion. Following this, the prototype parts are obtained and a wirewrap breadboard system is constructed.

2. Prototype Test Plan--A test plan to prove the concept of the system is developed and documented. A functional test of the wirewrap breadboard prototype at normal ambient temperature would be conducted to verify the design. After system operation is verified, further testing of the system at temperature and humidity extremes would be conducted.

3. Prototype Development--A redesign of the system would be made and documented on the basis of test result's. It would be iterated back to step 2 to be evaluated and retested.

4. Prototype Final Test and Acceptance--The system is given final testing and acceptance to complete the prototype design. Drawings and documentation would be brought up to date and finalized.

5. Layout of Printed Circuit Board and Manufacture--This step involves the process of moving from the wirewrap breadboard to a preproduction version. Here, the breadboard circuit design is translated into P.C. artwork. A P.C. board is created and a preproduction version of the sytem, complete in every way to all subsequent copies, is generated. The necessary destructive tests would be performed on this system version. Environmental prototype testing such as radiation and vacuum would be conducted by an outside vendor, with certificates of compliance and performance data provided. Following this, the remaining units are then fabricated and given nondestructive performance tests.

3.4.5 Power Regulation

As described earlier in the conceptual design section of this report, a pulse width modulated DC to DC power regulator would be used. The general design of this system would involve the following:

1. Circuit Electrical Parameters--The definition of the power regulator's performance and interface requirement would be made using inputs from battery and battery charge controller systems characterizations.

2. Method of Switching--The method of switching would involve examining the following tradeoffs:

- Speed of switching vs.
  - Efficiency

- Mass

- Cost

- Reliability

- Type of switch; field-effect transistors vs. bipolar chopping transistors

- Use of Large Scale and Medium Scale integration vs. Small Scale and Medium Scale integration discrete designs.

- Component resistivity analysis vs. efficiency and mass

- Use of Mil-Spec components vs. Industrial grade components

Choice of switching speed and overall system efficiency must be evaluated against performance level in the selection process. As switching frequency increases the size and heat requirements diminish, but so does efficiency relative to load. The designer must examine the load demand profile and select in relation to the aforementioned tradeoffs which approach would be best.

3. Control Mechanism—The selection of either analogue or digital control approach is made in conjunction with the battery control groups. This design function must be integrated with information from the battery charge controller, array and battery groups.

After the completion of the conceptual design tradeoffs, steps 2 through 5 of the preceding section would be used to complete the development of this subsystem.

3.4.6 Slip Rings and Deployment

These two systems have been grouped together as an individual set under the assumption that Solarex would rely on a vendor or vendors to perform this effort who have the required expertise in performing the design and development. A set of recommended steps for each systems development are identified below.

Slip Rings Design Steps:

1. Materials Design--Materials will be selected to be used in the fabrication of slip ring, contact brushes, shaft and bearing assembly.

2. Power Transfer--This process would include the determination of: (a) mechanical efficiency, (b) drive motor selection, (c) gear reduction design, (d) electrode contact pressure, and (e) lubrication requirements. A capacity to weight ratio analysis would be performed to minimize system weight, structural complexity and electrical capacity.

3. Structural Design Analysis--An analysis will be made of the slip ring design including a dynamic analysis of (a) movement inertia, and (b) vibrational stress on the arrays, bearings, shafts; and (c) gear train-assembly.

This analysis of materials and structural design will minimize potential damage and deformation during launch. Weight and volume tradeoffs would be conducted.

4. Vibration Analysis--Testing of prototype approaches would be conducted as needed.

It is generally assumed that in actual practice, existing designs, or even hardware, could be used and modified to reduce the amount of design effort. Solarex would not perform the work on the slip rings.

Deployment Design Steps:

1. Deployment Assembly Design and Concept--This effort will define the method of deployment and detail the structural requirements of the lazy tong assembly. The extensible booms and electrical circuitry for the system will also be designed at this point.

2. Storage/Deployment--This step would involve a detailed design of the assembly, method of storage inside the snuttle and deployment during placement into orbit.

3. Spring/Actuator System--The actuator system for the extension of the arrays in flight will be defined and designed.

4. Extensible Boom System--A dynamic analysis of the array boom assembly, motor drive housing with regard to such elements as deployment speed and boom length would be conducted.

5. Deployment Motor Selection--The required drive
motors, gear reduction ratios and mountings would be de-
fined and selected for the deployment system.

6. Component Integration--This step would involve
generating the assembly drawings and testing plans to verify
the overall deployment design of the system.

7. Component Stress Analysis--Specific component
parts of the deployment assembly would receive vibration
loading tests to establish whether or not the materials and
design would meet specifications.

As with the slip ring assembly, Solarex would resort to
vendors to provide the design and development of the
deployment subsystems.

3.5 Design Manpower/Cost Estimates

In tables 3-1 through 3-7 the Design manpower and cost
estimates are presented for all subsystems and design task
categories previously discussed. This analysis indicates the
following:

- Total manpower = 6099 man hours or 2.93 man years
  of design effort.
- Total Cost of Design = $133,305

In general the data presented indicates a fairly high
correlation between increased system complexity (i.e., mov-
ing from cell design to battery charge controller design)
and subsystem design cost.

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Table 3-1

Photovoltaic Cell Design Cost

Task Description	Man Hours	% Skill Level			
		AP	PT	TA	Sup
Light Determination	3.5	.5	.7	--	--
Interconnect Design	3.5	.5	.7	--	--
Power Requirement	7.0	.7	1.7	--	--
Cell Sizing	7.0	.5	1.4	--	.5
Surface Preparation	6.5	.5	1.0	.5	.2
Base Resistivity	8.5	.5	.9	.5	1.0
Front/Back Contact	13.0	1.4	1.5	1.5	--
Front Pattern	47.0	---	4.0	5.0	7.0
Cell Analysis	198.0	---	10.6	50.0	7.4
	295	4.6%	22.0%	57.0%	16.0%

Cost = $2,263

Cost & Overhead = $5,600

Table 3-2

Panel System Design Cost

Task Description	Man Hours	% Skill Level			
		AP	PT	TA	Sup
Coverslide Design	60	.5	6.0	8.0	1.5
Adhesive Interface Analysis & Testing	100	1.5	10.0	4.0	1.0
Interconnect & Wiring Design	180	5.5	11.0	12.	.5
Substrate Frame Design	120	2	6.0	7.0	.5
Panel Electrical Design	135	-	15.0	7.0	1.0
	595	9.5%	48%	38.0%	4.5%

Cost = $ 5,549

Cost & Overhead = $13,595

Table 3-3

Battery Design Cost

Task Description	Man Hours	% Skill Level			
		AP	PT	TA	Sup*
Preliminary Design Study	135	–	8.5	11.0	–
Battery Selection	125	–	8.5	9.0	–
Battery Enclosure Definition	100	2.0		8.0	–
Load Characterization	135	2.0	4.0	14.0	–
Terminal Voltage Analysis	75	.5	9.5	1.5	–
Load Variance Analysis	60	–	2.0	6.5	–
Weak Battery Strategy	90	1.5	10.5	–	–
	720	6.0%	43.0%	50%	1.0%

*Trace Amounts

Cost = $ 1,508

Cost & Overhead = $15,944

Table 3-4

Battery Charge Controller Design Cost

Task Description	Man Hours	% Skill Level			
		AP	PT	TA	Sup
Conceptual Design & Optimization	120	.6	2.5	1.5	.8
Prototype Test Plan and Concept Verification	600	1.0	10.0	12.0	6.0
Prototype Development	1220	3.7	21.0	12.5	8.0
Prototype Final Test and Acceptance	280	.9	6.4	11.0	-
P.C. Board Layout	50	-	.6	1.6	-
	2277	6.2	40.5	38.6%	14.8%

Cost = $19,572

Cost & Overhead = $47,952

Table 3-5

Power Regulation Design Cost

Task Description	Man Hours	% Skill Level			
		AP*	PT	TA	Sup
Determine Circuit and Electrical Parameters	200	−	6.0	13.5	4.5
Method of Switching	60	−	2.0	4.5	1.5
Current Limiting & Load Evaluation	130	−	7.0	8.0	2.0
Environmental Analysis	160	−	5.0	8.5	7.0
Component Selection	40	−	2.0	1.0	3.0
Test Plan & System Verification	74	−	2.0	9.0	3.5
Cabling and Inter-connecting	80	−	3.0	4.0	2.5
	744	1%	27 %	48%	24%

* Trace Amounts

Cost = $ 5,600

Cost plus Overhead = $13,713

Table 3-6

Slip Ring Assembly Design Cost

Task Description	Man Hours	% Skill Level			
		AP	PT	TA	Sup *
Materials Design	160	6.0	15.9	-	-
Power Transfer	280	12.5	24.8	-	-
Structural Design Analysis	180	6.0	19.0		
Vibration Analysis	118	-	14.8	-	-
	738	24.5%	74.5%	0	1%

*Trace Amounts

Cost = $ 8,205

Cost & Overhead = $20,102

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Table 3-7

Deployment Design Cost

Task Description	Man Hours	% Skill Level			
		AP	PT	TA	Sup
Deployment Assembly Design & Concept	159	2.0	6.8	10.0	3.2
Stowage	100	—	10.0	3.0	—
Spring/Actuator System	40	—	2.5	2.5	—
Extendible Boom Design	100	3.0	4.0	6.0	—
Deployment Motor Selection	30	—	2.0	5.0	.8
Component Integration	200	2.0	12.0	13.0	—
Stress Analysis & Modification	100	—	13.0	—	—
	730	7 %	50.3%	39%	4%

Cost = $ 6,695

Cost plus Overhead = $16,400

.3.6   Warranty Cost Determination

Warranties generally include only the value of the product delivered and not secondary damages that might be caused by the products failure or conditions which exceed those under which the warranty was issued. A warranty documents the guarantee offered by the manufacturer of the integrity of design, materials, workmanship, maintainability, reliability and suitability of the product in accordance with its specifications. Warranties historically have been used to state that the supplier will provide adequate material quality and good workmanship. It is commonly considered desireable to build in quality at the design and production phases in order to provide maximum operational life in order to lessen the probability of invoking warranty application.

A warranty can be almost anything a supplier and a customer want it to be. A warranty can simply state, "the product is free from defects in material and workmanship for ninety days" or it can be more complex including specific definitions of defects, procedures for processing warranty claims, and detailed warranty exclusions against all other warranties express or implied. Whatever the warranty is, it should be specifically written in the sales contract and clearly understood by both parties.

3.6.1 Disposition of Warranty Requirements

To minimize the risk associated with product defects, and to exert pressure on the supplier to eliminate defects,

accurate detailed design and operational specifications are
desired in addition to stipulations and approaches available
to the suppliers to reduce design, fabrication and opera-
tional cost.

Time elements must be specified to establish shops for
"in-house" repair and warehouse cost or to negotiate con-
tinued supplier repair at cost after the no charge portion of
the warranty expires. This is necessary to allow the supplier
to develop space for spare part storage and a maintenance net-
work that is economically manageable. In the case of a more com-
plex product, as with the satellite power system, it is considered
advisable to institute guarantees coupled with a predictive model
and commonly agreed upon characteristics associated with anti-
cipated system degradation such as effects of radiation, thermal
cycling losses, shadowing component losses to the panels, and
other unique factors.

It should be made mutually understandable to both parties
involved in the development, fabrication and eventual deploy-
ment of the system, the extent to which both parties are contingent-
ly dependent upon each other in providing useful and
efficient channels of communication in order to expedite the
repair sequence of particular failures. These factors must
be considered and implemented, so that a cost effective plan
of action for the disposition of spare parts, logistics of
repairs and maintenance can be mutually agreed upon. In some

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instances, both user and supplier may find it is more cost
effective to include maintenance time costs and guarantees
the warranty, assuming the user does not wish to perform
his own repairs.

The following factors must be taken into consideration
in order to evaluate and decide whether or not acceptance of
contract and potential cost/manpower risk is beyond the
capability of the supplier:

- Accountability of the buyer to furnish adequate
  fiscal management thus minimizing direct
  risk to the supplier in the form of unnecessary
  operating overhead, physical plant, work-force, and
  warehousing cost.

- Operation plan

- Type of warranty desired

- Usefulness of warranty elements--related to final
  cost measurability

- Plan for accurate maintenance of warranty records
  and communication

- Accessibility of supplier to records and opera-
  tional/maintenance findings

- Flight repair training plans

- Cost of warranty

- Predicted cost of processing claims

- Repair turnaround and transit times

Warranty cost is conventionally determined by in-
creasing the selling price to cover the predicted costs
associated with repair or replacements of the defective
components.

3.6.2 Small Order System Performance Clauses

A standard Solarex policy applied to small system
contracts is to repair or replace free of charge any defective
component which is returned to the plant. These performance
clauses are included in normal small order system con-
tracts. However, in the following situation, this conven-
tional approach to claims processing would not prove
prudent considering the system's complexity, management
of subcontractors and warranty/reliability requirements.
In considering the total amount of capital involvement of
such a project, some new ground may need be covered in
order to realize an equitable plan to assure minimization
of risk.

Some factors to be considered are as follows:

- Investigate the feasibility of insuring the system
  against unpredictable failures.

- Application of no-fault clauses in the event both
  parties discover unforeseen risks or hazards.

3.7 Approach to Documentation

In a relatively small commercial organization, such as
Solarex, the print control system and approval methods are
not extensive. Within this subsection reference is made

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directly to the document control section (QAP-120,rev A) of
the Solarex Quality Assurance manual.

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Document Control

SCOPE

The purpose of this procedure is to describe the control of
documentation generated and controlled by Solarex, but not
including the special handling of documents which require
national security classification. Such documents are the
subject of a separate procedure.

REFERENCED DOCUMENTS

The following documents may be used as guides and as supple-
mental information to this procedure:

    MIL-D-1000, Engineering Drawings and Lists

    MIL-STD-100, Engineering Drawings and Practices

    MIL-STD-480, Configuration Control

DEFINITIONS

DOCUMENT

Any drawing, list of materials, parts list, test procedure,
specification, instruction book, printed circuit master, or
copy of such.

ACTIVITY

Any division, directorate, department, section, group, or
engineer responsible for a job.

REVISION

An action by which a document is altered.

SIGNED-OFF DOCUMENT

Any document which has been properly prepared and contains all
of the required signatures. Documents will be classified into
one of four levels as follows:

S - Sketches and Preliminary Information

C - Conceptual and Developmental Design

P - Pre-Production Prototype

M - Manufacturing

Signature requirements are usualy as follows:

LEVEL

	M	P	C	S
Originator	X	X	X	X
Checker (where applicable)	X	X		
Electrical and/or Mechanical Engineer	X	X	X	
Project Manager	X			
Quality Control Engineer	X	*	*	
Reliability Engineer	*	*	*	
Customer Representative	*	*	*	

* = As Required by Project

Signed-off documents are considered appropriate and adequate
for procurement, fabrication, quality assurance, inspection,
drawing control, and documentation delivery requirements to
the level approved. The combination of a signed-off document

and appropriate signed-off ECN(s) is the same as a Signed-off document.

ENGINEERING CHANGE NOTICE

An ECN (Engineering Change Notice) is a document which authorizes revisions to documents. An ECN is a signed-off document as defined by this procedure and has the same signature requirements as the document which is to be changed.

NUMBERING PROCEDURE

ORIGINAL DOCUMENT NUMBERS

It is the responsibility of Document Control to keep a log and assign document numbers. The originator of a document obtains a number for a document by supplying the following information to Document Control:

(a)	Title of Document	(c)	Responsible Engineer
(b)	Originator	(d)	Date of Origination Document

ECN (Engineering Change Notice) Numbers

It is Document Control's responsibility to maintain a log of ECN's by number and to assure that the proper approvals have been obtained prior to incorporation into any approved drawing.

RELEASE PROCEDURE

The completion of documentation sign-off as shown above signifies readiness for release for production, procurements, delivery to customer, or other approved usage to the level defined.

WITHDRAWAL PROCEDURE

It is the responsibility of the Cognizant Manager to maintain control and Quality Assurance to conduct an audit of items obtained from Document Control. All prints should be destroyed after their intended use or at any time they become mutilated or illegible.

ORIGINALS

Original Documents (signed or unsigned) may not be removed from the document control area except for the purpose of revision in accordance with ECN procedure, or for production.

REPRODUCTIONS

Marking of Reproductions

All prints will be date stamped near the title block, showing the date the print was made. A reference to applicable ECN(s) will also be included. Non-reproducable copies of signed-off documents may be requested by any authorized person. Unless otherwise specified or if not specified, the latest revision, including applicable ECN(s) will be supplied on all requests for documents.

Disposition of Reproductions

It is the responsibility of the using activity to ensure that prints made for manufacturing purposes are properly disposed of immediately after use. No one is authorized to retain copies of such documents,

unless another "Production Run" to the same revision
is pending.

REPRODUCIBLE REPRODUCTION

Withdrawal of reproducible copies of signed-off documents
will be accomplished by a memorandum approved by the Cogni-
zant Manager and forwarded to Document Control. This memo-
randum must contain the following information:

(a)   Document Numbers

(b)   Revision Letters

(c)   Type of Reproducible Copy required

(d)   Request Date

(e)   Reason for Request

(f)   Quantity of copies of each document

A typical reason for removal of documents of this type is
for required delivery of reproducible drawings to the customer.

REPRODUCTION OF PRINTED WIRING MASTERS FOR SHIPMENT

Printed Wiring Masters, positives and negatives, are con-
sidered proprietary information and under no circumstances
should be released from company control. When contractual
obligations require the shipment of printed wiring masters,
the following procedure must be followed:

(a)   Reproduce the Masters utilizing a photographic
      process on material as specified by the contract.
      If there is no material specified, a photo-
      sensitive mylar base material should be used.

(b)   Full scale (1:1) reproduction including registra-
      tion marks should be made.

(c)   For two-sided masters, both sides should be
      included on the same format if the size permits.
      Where size is prohibitive, sheet one and two is
      acceptable.

(d)   The format should not exceed 61 cm x 51 cm.

(e)   The format must contain a border, title block,
      application block, and revision block as found
      on standard drawing formats.

(f)   All applicable information pertaining to the
      format and process noted must be properly filled
      in.

(g)   The reproduction must contain the same drawing
      number as the Printed Wiring Master.

<u>ENGINEERING CHANGE NOTICE PROCEDURE</u>

This procedure outlines the control of changes to signed-off
documents. The scope of this procedure dictates the necessary
control of ECN's from the preparation of the ECN through in-
corporation of the required change on the original document,
and then the storage and distribution of this information.
The Engineering Change Notice (ECN) is the document which,
when approved, authorizes Drafting to make revisions to
original documents. This approved ECN also authorizes Engi-
neering, Quality Assurance, and Project Services to take
appropriate action, since it becomes an integral part of a

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document pending the revision of the document.

PREPARATION OF ECN

Any person may suggest or request a change by originating a
"draft" copy of an ECN and forwarding same to the Project
Engineer for completion and validation. All ECN's, however,
must be approved by the cognizant personnel as described a-
bove. All changes to be incorporated must be fully described
on the ECN, giving details of the change what the document
presently shows, and the location of the change on the format.
For extensive changes use the ECN continuation sheet or a
plain piece of paper as an ECN continuation sheet or, if
necessary, obtain a reproducible print of the document and
mark the required changes on the print. This print should
then be attached to the ECN for distribution. When using a
print as part of the ECN, there must be sufficient marking
above the title block to indicate its use. This marking
should include:

    (a)   This print is part of ECN number_____.

    (b)   Date of ECN

    (c)   Page___of____.

The original document number must be lined through or removed
from the reproducible copy when used for ECN purposes.

Initiation

    It is preferable to prepare one ECN for any one

    change. This provides a convenient reference and

    check tool for all drawings affected by a specific

change. Additional, supplementary or multiple ECN's
may affect any change but should be avoided where
possible.

Completeness

A determination must be made by the project engineer
that all documents involved or directly affected by
any change are included in that ECN. For instance,
the change of a resistor value or location to correct
an erroneous output could influence the schematic,
assembly drawing, parts list, wire list, printed circuit board
layout, films, silkscreen, test procedures, relia-
bility prediction, etc. Assurance that recognition
of all impacted functions and documents has been
attained, requires very thorough investigation.

CLASSIFICATION OF ECN's

Each ECN shall be assigned the appropriate classification by
the originator in accordance with the definitions shown below.

Class I Engineering Change

An engineering change shall be classified class I when
one or more of the factors listed below (subparagraphs
(a) or (b) or any factor(s) listed under (c), (d), or
(e) is affected:

    (a)   The functional or allocated configuration
           identification.

    (b)   The product configuration identification

as contractually specified excluding referenced drawings.

(c) Technical requirements below contained in the product configuration identification, including referenced drawings as contractually specified.

1) Performance outside stated tolerance

2) Reliability, maintainability or survivability outside stated tolerance.

3) Weight, balance, moment of inertia.

4) Interface characteristics.

(d) Non-technical contractual provisions.

1) Fee

2) Incentives

3) Cost

4) Schedules or deliveries

5) Guarantees or warranties

(e) Other factors

1) Government furnished equipment (G.F.E.)

2) Safety

3) Electromagnetic characteristics

4) Operational, test or maintenance computer programs

5) Compatibility with support equipment, trainers or training devices/equipment.

6) Configuration modifications to the extent that retrofit action would be taken.

7) Delivered operation and maintenance manuals for which adequate change/ revision funding is not on existing con- tracts.

8) Pre-set adjustments or schedules affect- ing operating limits or performance to such extent as to require assignment of a new identification number.

9) Interchangeability, substitutability or replacibility.

10) Sources of units or repairable items at any level defined by source control drawings.

Class II Engineering Change

An engineering change shall be classified class II when it does not fall within the definition of a class I engineering change.

Examples of a class II engineering change are:

(a) a change in documentation only (e.g., correction of errors, addition of clarifying notes or views)

Or

(b) a change in hardware (e.g., substitution of an alternative material which does not affect

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any factor listed above.)

DISTRIBUTION OF ECN's

ECN originals are filed in the Document Control Center.
Copies are distributed as follows:

  (a) To recipients of "automatic" distribution.

  (b) To others as indicated on ECN.

  (c) To others as requested by the Cognizant Manager.

  (d) Upon individual request.

INCORPORATION OF ECN's

Document control will provide a copy of the ECN to Drafting,
along with the original documents, for revision. The Draft-
ing Department will make the required revisions to the original
document and return the document to the Document Control Center.

Revision Block

The revision block on the original document will be up-
dated at the time of revision to include the revision
letter, ECN Number, Date, and Approval. In addition,
other change details may be included space permitting.

DISTRIBUTION OF REVISED DOCUMENTS

After incorporation of the ECN(s) into the original documents,
the Document Control Center will make prints for distribution.
This distribution will be the same as the ECN.

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In general, design documentation is correlated with the three design levels mentioned earlier in Section 3. The characteristics of the documentation at each design level are summarized below:

- Design Level No. 1--Documents generated at this level of activity would consist of performance specifications, sketches of initial design approaches, functional drawings of systems and component subsystems. All spacecraft launch and flight characteristics would be translated into performance and operational specifications. This design effort would be completed by a summary report rendering the best alternate approaches.

- Design Level No. 2--Prototype designs, test plans and test data would be generated. Resultant performance data would be documented for evaluation and finalizing the engineering drawings.

- Design Level No. 3--This level of design documentation would concentrate on such aspects as generating operating instructions, service and assembly manuals and drawings. The required production parts and materials lists and specifications would be generated here. The warranty agreement would be evaluated by both buyer and supplier and then documented. QA plans for testing panels and

other subsystems would be developed.

In general, recommendations for reducing documentation cost would be to limit the type, amount and degree of distribution of design and specification documentaion. Distribution of documents for design purposes would be to key individuals within the design and development groups.

In a more general sense, reduction of production related documentation cost could be achieved in the following ways:

- Reduce the detail of performance classification of solar cells. That is, avoid documenting each individual item, but rather sort and aggregate cells into performance ranges; this approach also applies to panel Q.A. documentation to a lesser extent.

- Limit production and process control documentation. This aspect of documentation can become quite labor consuming, and to some extent does not impact directly on the ultimate outcome of the product. Moreover, in a situation where the product is not overly complex, much of this could be under the direct supervision of the production manager. Emphasis should be placed on documenting the final outcome.

In situations where product documentation is already in existence, it is recommended that this material be used, rather than instituting policies that require process/production steps. Additionally, by adopting a minimum specification/documentation approach the manufacturer is provided

with the latitude to make adjustments to production without the weight of large documentation overhead.

Additional requirements may be incumbent on the vendors when a definite time line must be followed. This would usually involve the submission of a GANTT or PERT charts plotting the progress of their effort. These documents would in turn be applied to the in-house documents of the system flowplan. This action is generally not used unless the project is extremely complex and requires the administration of diverse groups of subcontractors. In order to deal effectively with a project in a timely manner, identification of weak links in the system flow would be of assistance. The rationale behind employing such approaches is in allowing a documented procedure to assist in guiding the movement of a system through its production cycle.

3.8 Documentation Manpower/Cost Estimates

In Table 3-8 the estimated documentation manpower and cost is broken out by skill level category and subsystem. Four general categories of documentation (principally assocciated with design and development) manpower were:

Specification Generation	24%
Drafting and Related Effort	42%
Assembly Design	20%
Piece Part Lists; Programming; Graphics and all Other	14%

Table 3-8

Documentation Cost

Task Description	Man Hours	Dollars/Skill Level			
		AP	PT	TA	Sup
Cells	132	190	702	238	81
Panels	165	85	770	615	-
Power Regulation	610	-	721	1538	2184
Battery Charge Controller	329	84	1578	769	288
Batteries	280	1200	1538	231	96
Slip Ring	180	-	193	769	288
Deployment	270	-	384	769	624
	1966	1559	5886	4929	3561

Cost = $15,935
Cost Plus Overhead = $39,040
Plus Added Cost = $40,734

3.9 Approach to Fabrication and R & QA

3.9.1 Facilities and Skills

The facilities required to fabricate the majority of the component subsystems do not require large amounts of physical space. All the necessary evaporation equipment, diffusion furnaces, ovens and other equipment exist at Solarex, for cell production and panel assembly. The present plan would be to take advantage of the present production facility with the addition of added area for the system assembly and bench testing and for storage of the components parts. It is estimated that an additional 93 m^2 area for this would be adequate.

Emphasis would be placed on backing away from customary approaches in fabricating this system such as the use of clean rooms and the like. Such methods, while having customary application in space qualified missions, must be examined for their validity from a commercial standpoint, especially when considering a maintainable system. In an effort to diminish capital intensive factors in production of space power systems, it may be worthwhile to investigate the efficacy of clean rooms relative to reliability. Does the cost of such facilities justify their use in terms of performance? The use of clean rooms may be found to be more of psychological manifestation that signals to the employee the apparent importance c the work and its purpose rather than its use in elevating system reliability.

In a commercial approach the use of such exotic facilities
is looked on as an inefficient use of physical space, and
its validity needs to be proved before implementation.
The pattern of logic in determining their value would be
to identify empirically from a worst-case situation, then
improve until a level of facilities modification sufficient
to cause a real impact on performance was realized, rather
than the opposite. For cell and panel fabrication use of
such facilities does not appear necessary. Another system,
such as smaller plastic airtight chambers for clean storage,
laminar flow assembly hoods and vacuum cleaning equipment
would work quite adequately in most, if not all, instances
of fabrication.

More emphasis should be directed to developing a
management and labor force with the versatility to move
rapidly from one project to another, which would reduce a
large production cost driver, i.e., misuse of time and facili-
ties. This factor is very important in any commercial
setting where production throughput can strongly impact
the company's ability to increase sales and grow.

It is recommended that for production to prove economical,
it must attract a large enough demand of standard products.

The interface between the design and production groups
in setting up facilities to fabricate such a system would be
to combine system requirements with equipment development.

Because of the nature of the project the production engineer-
ing group would have to examine what is necessary in terms of
special test equipment, fabrication jigs, and other equip-
ment. Decisions about whether and to what extent equipment
would increase production flow would be made.

3.9.2 Training and Skill Levels

The emphasis and approach to fabricating this system
would be to utilize the skill levels of Solarex's present
work force. Common to most commercial organizations and
the operation of a production facility are the ever changing
tradeoffs between skills of the workers, impact of unionism,
intermediate and full automation and the product demand.
Characteristically, any commercial organization is devoted
to one salient purpose, which is to realize a profit. The
approaches taken from one company to the next are not homo-
geneous, and vary greatly based on the methods, philosophies
and management skills that are embodied by the company. A
favored strategy is to minimize the use of skilled labor,
increase automation and maintain production control. Special
orders and exotic fabrication are not generally placed in
the hands of a mass-production system.

At Solarex, the production of solar cells at a high
quality level, is not so much a function of the employee skill
levels as it is the maintenance and control imposed by managers
that understand the technology. An individual task, such as

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operating an evaporation dome, does not require extensive
education to operate. Typically a new employee can be trained
to operate one in a couple of days. In a production facility
which is still labor intensive to a large degree, minimiza-
tion of the skill level of the work force also tends to re-
duce labor cost. In the solar cell fabrication phase, stand-
ard production and Q.A. approaches would be undertaken. How-
ever, the array assembly would be conducted by the panel
specialty development line because of the low volume of pro-
duction. This unit is composed of a skilled group of engi-
neers and technicians which is customarily involved in pro-
totype development and limited production.

The other systems are quite different in some respects.
For the most part, for a small number of copies, the projects
are labor intensive and require more skill. These fabrication
teams would consist largely of a few experienced technicians
with a wide range of related skills. Otherwise, the majority
of the effort would be accomplished by engineers and technicians
performing the appropriate test sequences. Battery fabrication
procedures and facilities would have to be separated from the
rest of production. Monitoring of the batteries could be con-
ducted in a relatively small area by a few cognizant technicians
with supervision.

In those instances where the company's in-house technical
resources are limited, the addition of aerospace engineers for
the design, fabrication and testing would be necessary.

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Additionally, design consultants would be employed.

3.9.3 Product Engineering

Conventional wisdom associated with the concept of product engineering is that it is identified with small refurbishments that alter in some minor way the system by improving reliability or performance once the system is in operation. As earlier editions of a particular item are placed into various conditions, errors in design or fabrication not previously uncovered in the prototype or testing of the systems begin to show themselves. Here product engineering involves making the needed design modifications as they occur in conjunction with each new version of the system and to provide these improvements to users. A product engineering philosophy usually implies that a system can appreciate in value, flexibility and reliability by modifying it through maintenance and replacements which would utilize improved materials and fabrication changes. It is generally believed that this approach can enhance system value and reliability without significant increases in cost.

The concept of product engineering is to provide the same basic system that the original design calls for with the exception that the manufacturer is able to continuously examine the cost to fabricate against performance. When a modification simplifies production without altering significantly the ultimate outcome it behooves the manufacturer to do so.

Product engineering as viewed at Solarex comprises the following:

- The rectifying of minor deficiences during system development.

- The application of alternate production methods to achieve the same outcome for less cost.

- The ability to implement engineering improvements on a production item after it has been placed in service.

- Institute design changes that improve producibility of the product.

3.10 Subsystem Fabrication and Q.A.

The following subsections are divided into subsystem categories. In each subsystem the QA process is merged with the fabrication steps. Flowchart and stepwise descriptions are used extensively to portray dynamically how the process of producing this system would come about.

The symbols employed in these flowcharts follow standard flowchart methods. Symbols of primary importance are as follows:
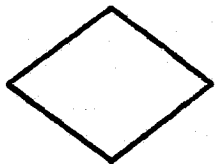
= A diamond indicates a decision and subsequent path of information or product based upon that decision point.

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→ ◼ An arrow indicates the direction of
   product or information flow.

◼ An open arrow indicates a **sequential**
   off page connection to/from an off page
   open arrow containing the same
   numerical value.

◼ Open circle indicates as non-sequential
   connection to/from an off page open
   circle containing the same numerical
   value.

3.10.1 Solar Cells

Figure 3-12 presents a flowchart of this process as it
functions dynamically. Indigenous to this flow diagram
are ten process and Q.A. steps used in the fabrication of
a commercial Solarex solar cell:

1. Incoming Silicon and Materials Q.A.--Incoming silicon
is tested for base resistivity using a hot probe technique,
and for whether it is N or P type silicon. From this determi-
nation the material is either rejected or accepted. Rejected
material is returned to shipping and receiving and shipped
to the vendor. The accepted silicon is placed in stock in
preparation for the next process step.

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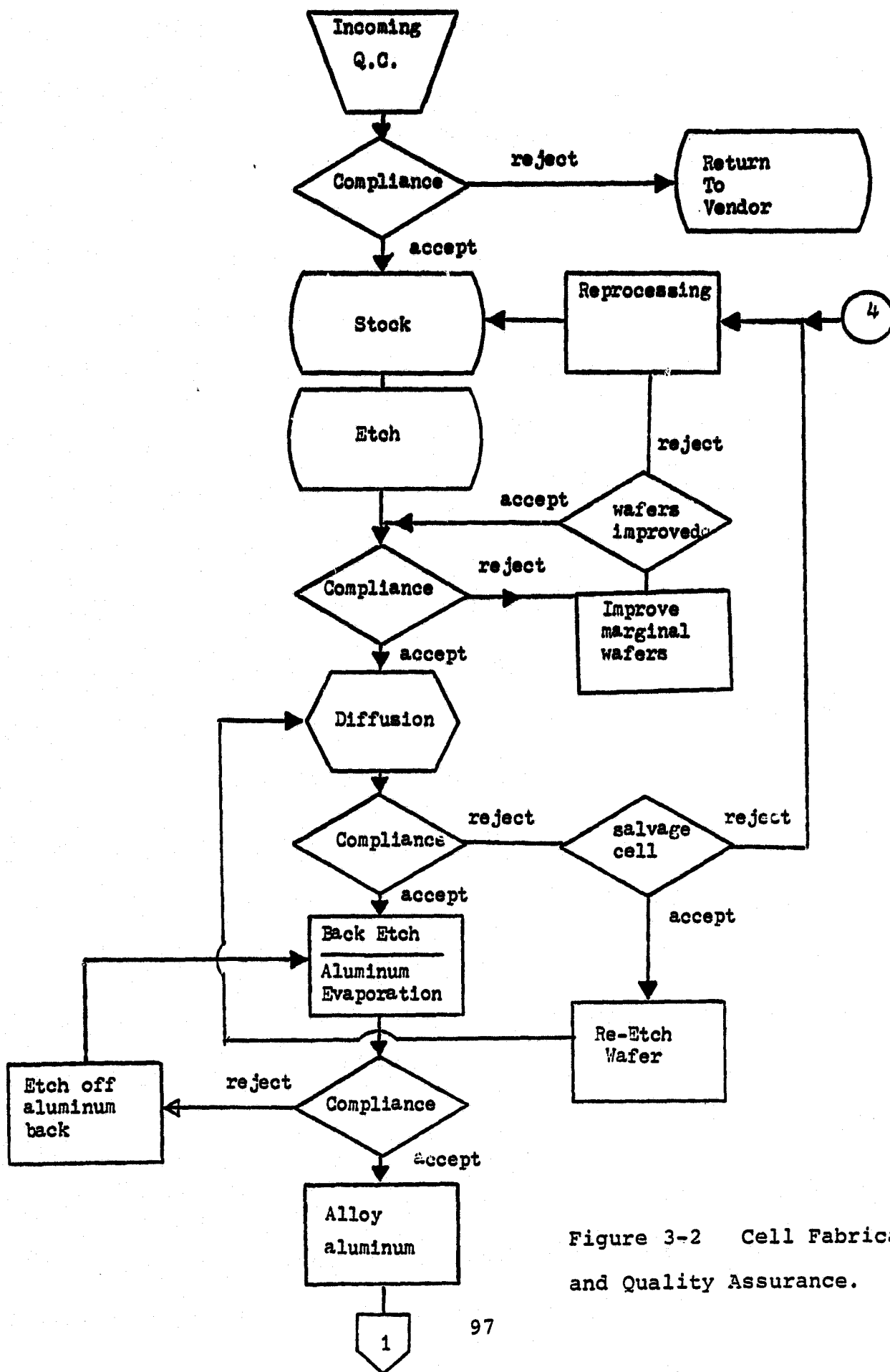
Figure 3-2   Cell Fabrication and Quality Assurance.

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Figure 3-2 (continued)

Figure 3-2 (continued)
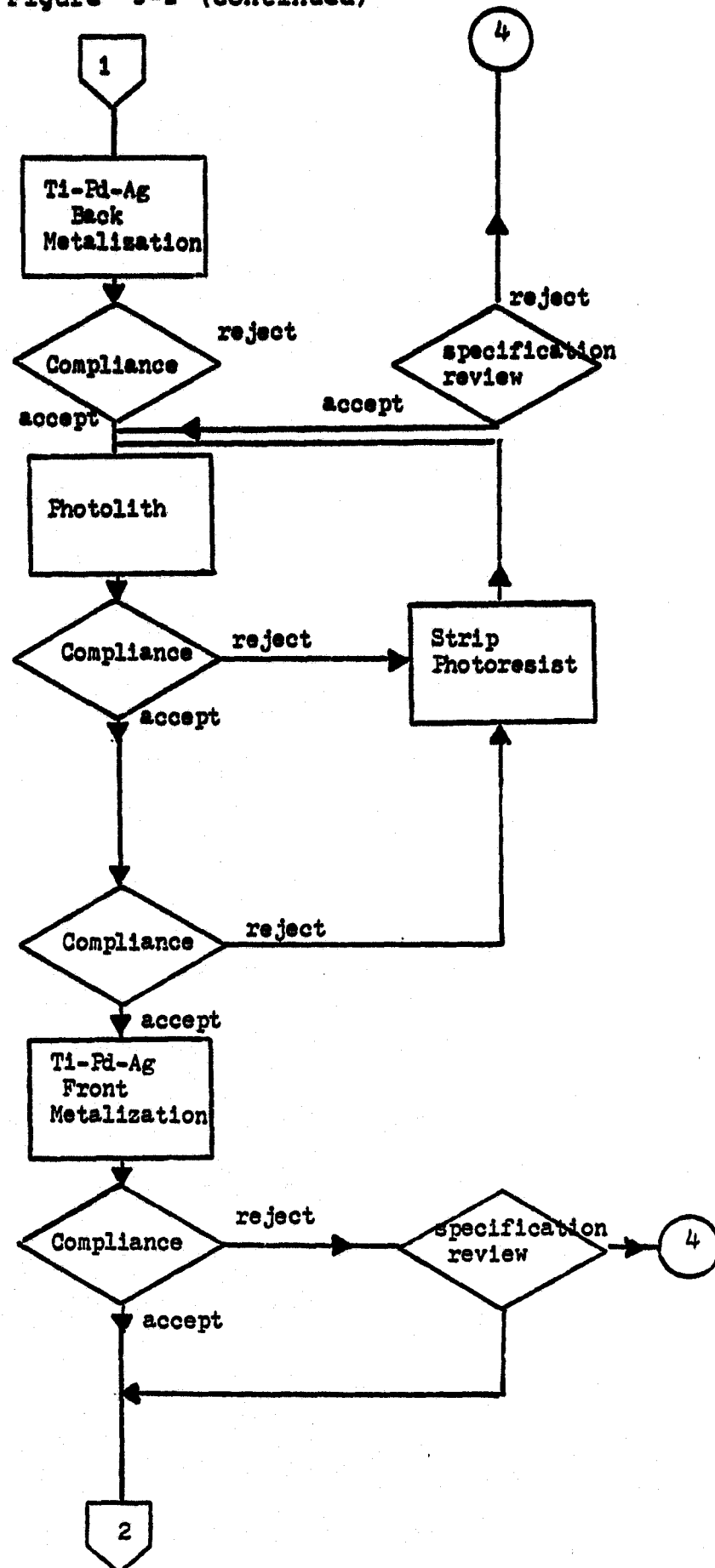
Figure 3-2 (continued)
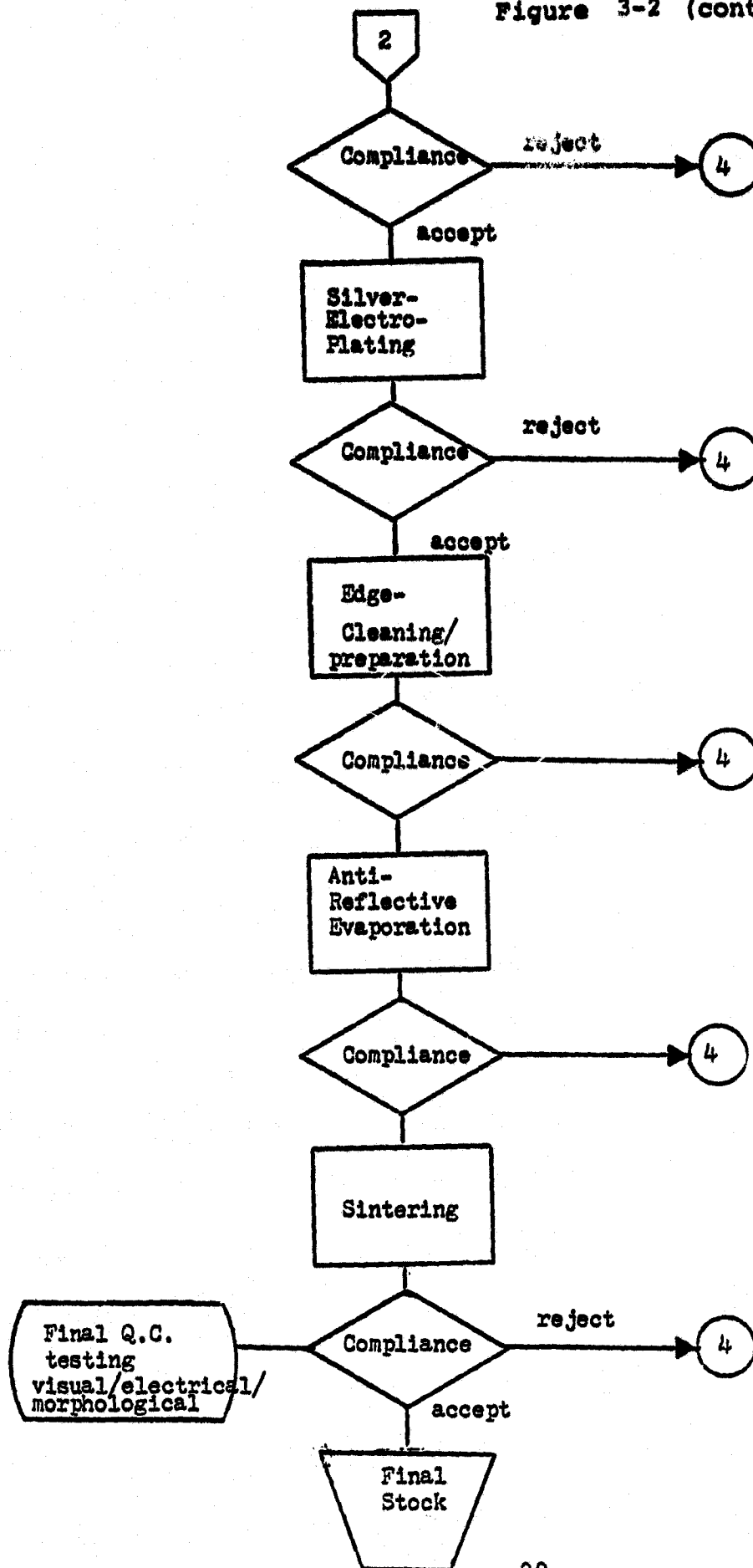
2. Etch--The silicon is drawn from stock and placed in an etch bath using the prescribed temperature and etching solution. The type of etchant varies in some instances as a function of the type of silicon (crystalline orientation and other factors). Following the etch processes, in-line Q.A. will sample the etched silicon for surface and thickness conformity. From this point the material is placed into stock or passed directly on to be processed, dependent upon the production status of the rest of the line. Material that fails criteria must be evaluated for application to other functions. The rejected material may still be useful for other things such as reusing it for semicrystalline applications, watch cells, diodes or other R&D functions which help to buffer the cost of the original material against a complete capital loss.

3. Diffusion--After completion of a diffusion operation the wafers are then sampled from different segments of the diffusion tube and junction formation and sheet resistance are measured.

4. Aluminum Backfield Formation--The backfield formation in a commercial cell can be fabricated any number of ways. Presently, the method used is by vacuum evaporation. The Q.A. function performed here is a simple visual inspection of the back surface to meet with coloration and texture criteria. Such in line tests allow the production manager useful input

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into needed equipment repairs and maintenance or modification of the process to bring production back under control.

5. Back Surface Metalization--The Ti-Pd-Ag metals are then applied to the back surface. The metals are sample tested for adhesion to the aluminum to determine whether or not a clean bonding of the metal interface is made. A tape pull test on a control monitor is used to determine the bond.

6. Photolithography--This step is associated with applying the photoresist, baking it, and exposing the photoresist to the prescribed pattern via a collimated UV light source. In all of these functions data is logged and evaluated by Q.A. to determine the effectiveness of the exposure, alteration of resist composition and bake time. Application of too much or too little photoresist or improper exposure will negatively affect all subsequent steps of metalization and fabrication. Q.A. actively culls out poor bus pattern set-up. This function is necessary to insure good metalization in subsequent steps. Cells are inspected to determine the presence of gridline flaws. This function is necessary to determine effects of gridline delamination and grid bus contact quality.

7. Front Surface Metalization--Similar to back contact preparation, after metalization is applied, a sample tape pull test of the metalization is necessary to determine the integrity of the contact's metalization.

8. Silver Plating--After the cells are metalized the bulk conductive material is applied. The necessary Q.A. functions associated with this are inspection of plating bath PH and chemical composition, and sample visual inspection of plating thickness.

9. Anti-Reflective Coating--A visual inspection of cells for conformity with a color standard is performed. A proper interference index is necessary to obtain high matching for the silicone adhesive and glass interface. Occasional lot samples are periodically tested for spectral response.

10. Final Q.A.--After the cells have come from the thermal annealing process they are given a final inspection. The cells are sorted on the basis of load tests into groups based on their performance. Those cells that do not conform to standards are returned for reprocessing and/or scrapped dependent upon their physical condition. In addition occasional samples are taken for pull tests on the contact pads.

Upon completion of these fabrication and quality control functions the cells are coded and sent to stock relative to product designation and performance classification. From this point the next phase of fabrication is undertaken.

3.10.2 Panel System

Figure 3-4 shows a flowchart of the panel fabrication process as conceived to fabricate a set of panels for this
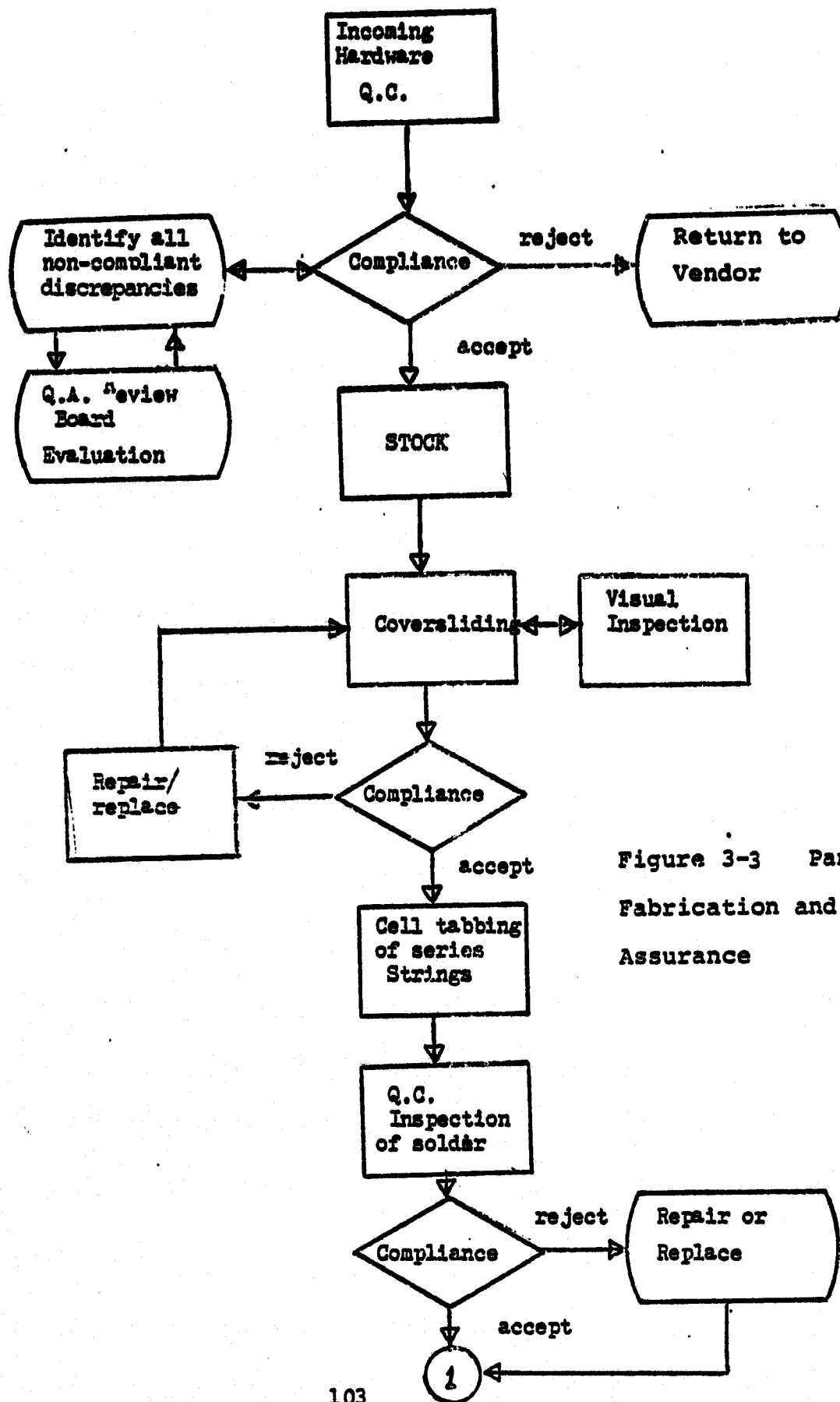
Figure 3-3   Panel Fabrication and Quality Assurance

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Figure 3-3 (continued)

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                    ( 1 )
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                      ▼
      ┌─────────────┐        ┌─────────────┐
      │ Cell strings│◄───────│ Realignment │
      │     to      │        └──────┬──────┘
      │  substrate  │               │
      │   laydown   │               │
      └──────┬──────┘               │
             │                      │
             ▼                      │
          ◇ ?         reject        │
        Alignment ─────────────────►┘
          check
             │
             ▼
      ┌─────────────┐
      │  Pumpdown   │
      │  (de-air)   │
      └──────┬──────┘
             │
             ▼
           ◇            reject    ┌──────────────────┐
        Compliance ─────────────►│  Repair/replace  │
                                  │ ---------------- │
             │                    │   Q.A Review     │
             │        accept      └────────┬─────────┘
             ◄─────────────────────────────┘
             ▼
      ┌─────────────┐
      │             │
      │    Stock    │
      │             │
      └──────┬──────┘
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      │  Shipping   │
      │    Q.A.     │
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      │  Customer   │
      └─────────────┘
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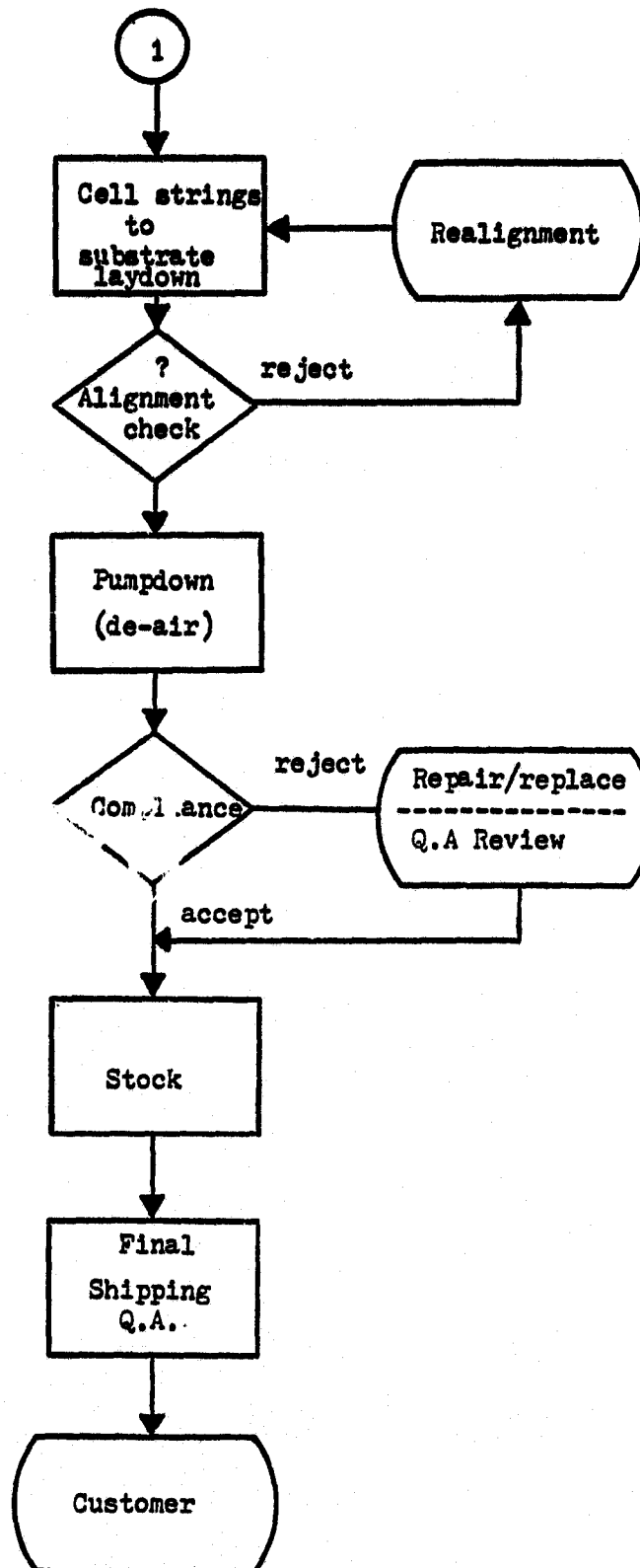
array system. Six major process and Q.A. steps have been identified:

1. Coversliding—After the cells and coverslides are pulled from stock they are initially inspected and matched to the design specification criteria. The needed materials for bonding are also procured and placed in a vacuum chamber and outgassed to eliminate bubbles from the adhesive. Following this, the component parts are then assembled. Measured amounts of the adhesive are applied to the solar cell and spread uniformly and the coverslide is attached and aligned so that tabs and coverglass slots are properly situated. After this they are inspected for bubbles and large pieces of particulate matter. If no indication of defect is found then the cell coverglass is heat cured.

2. Cell Tabbing—The cells are then placed into solder jigs and tab interconnects are laid down and soldered. After completion of a substring of cells the solder joints are then placed under a stereoscope and inspected for cold solder contacts. Cell strings having bad interconnects are returned for repair or replacement.

3. Cell String Attachment to Substrate—As a full compliment of a series string is completed the diodes are attached and inspected,then placed into a laydown jig that will hold them in place. Adhesives are applied and contact is formed.

A visual inspection is performed to establish if the cells are uniformly placed on the substrate.

4. Pumpdown--After cells are applied they are then placed in a panel pumpdown chamber and the adhesive is out-gassed followed immediately by heat curing.

A final inspection using a flash simulation would be performed to derive the panel's output and efficiency. Following this, if a cell failure is found they are returned and repaired. The completed panels are then sent to stock or shipped dependent on the procedure to be followed.

3.10.3 Battery System

Figure 3-4 shows the flowchart of the battery subsystem acceptance testing procedure. This approach employs a series of iterations of testing on individual Ni Cd cells. This approach assumes an avionic battery has passed the original design stage and was found acceptable and safe under the appropriate operating conditions.

The only actual fabrication would be involved with construction of the containment system and configuration. The containment itself would be prototyped in-house. However, production models of the system would be subcontracted to a vendor for fabrication.

The procedure for the fabrication/assembly of the battery subsystem would involve the following tasks:

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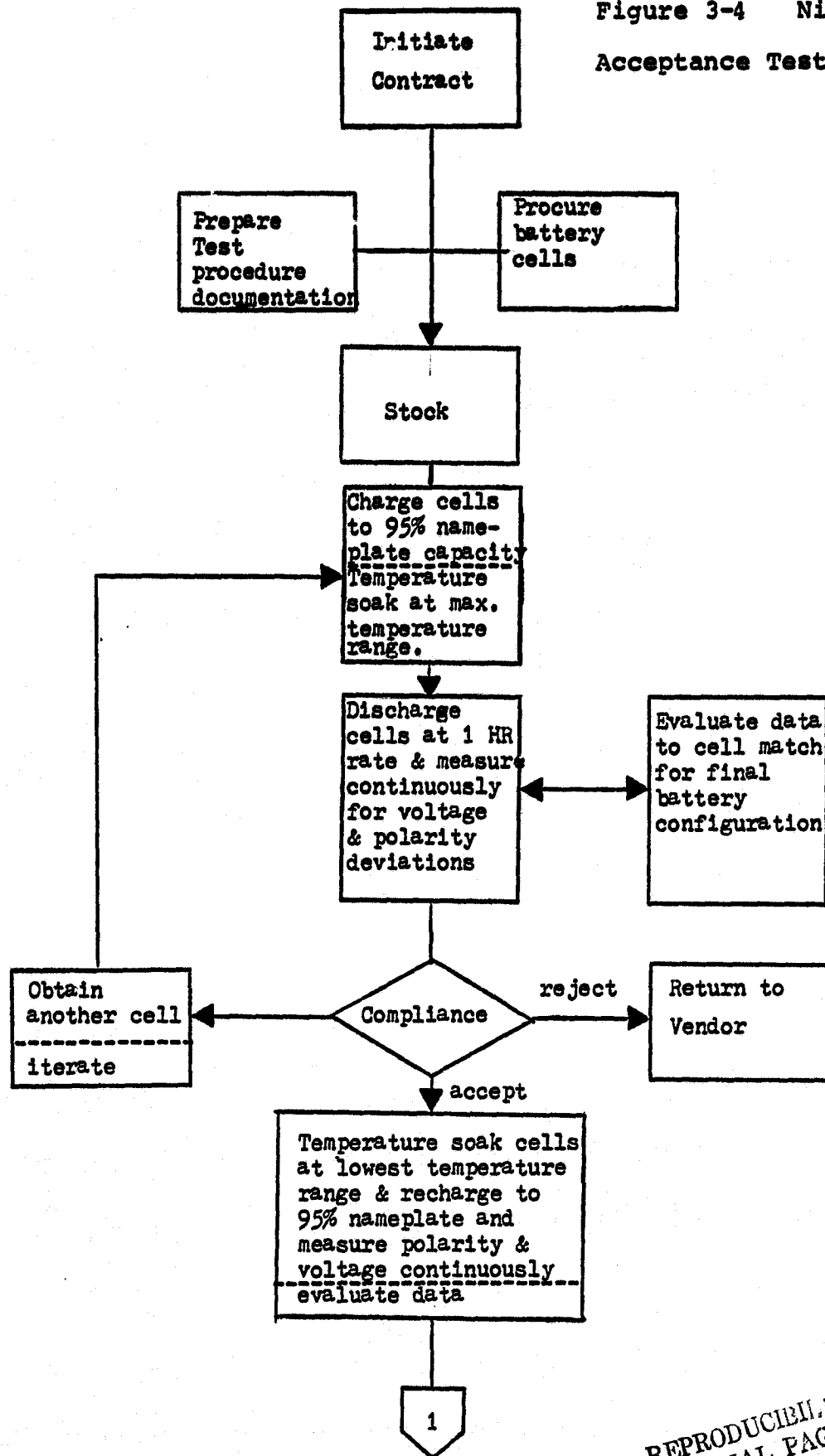Figure 3-4   Ni Cd Battery Acceptance Testing Approach.

Figure 3-4   (continued)
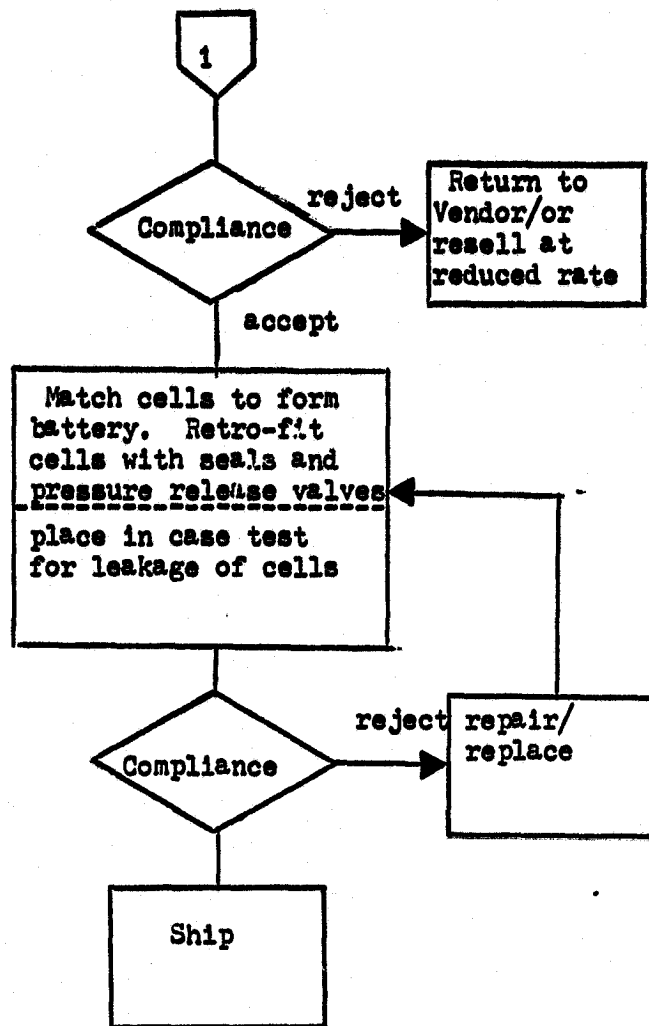
1. A set of cells would be procured from a vendor dependent upon design specification. These cells would receive an initial incoming Q.A. check for cracks or defective workmanship. From this the cells would be placed in stock in lieu of the forthcoming testing phase.

2. After the initial procurement, the Ni Cd cells would be drawn from stock and charged to 95% of nameplate capacity, then temperature soaked for a duration of time that would be verified from the design specification. It is estimated that the soaking time period may be as long as 24 hours. This would first be performed at the upper predicted temperature of the cell operating in the spacecraft.

3. The cells would then be discharged at a 1 hour rate and continuously measured for voltage and polarity deviations. This task could be performed manually using a technician or the test sequence could be performed using a microcomputer test station with online programs that would collect the data and graph the results. The cell would be tested in accordance to design test specification. These specifications would establish the minimum allowable cutoff for temperature and voltage.

These data will be evaluated by the designer and Q.A. personnel to determine what will be accepted or rejected. Those cells that do not meet this initial acceptance test will be returned to the vendor or sold for other applications if possible.

4. The same procedure will be repeated from Step 3 at the lowest predicted temperature the battery would be expected to incur.

5. After a final set of cells has passed acceptance testing the process of correlating the remaining sample of cells would be undertaken. This matching process would also be based on the tolerances established during the design phase specification. From these matches the cells would be placed in containers such as described in the conceptual design and tested for operation and for outgassing effect. In turn, rejected battery units would be diagnosed for the failure mode and the indicated replacement or repair performed.

6. The system would be placed in stock or shipped to the next destination depending on the requirements of the program.

3.10.4 Battery Charge Controller and Power Regulator

Figure 3-5 shows the flowchart plan for fabrication and inspection of these two systems. However, Solarex would subcontract these two systems to a vendor to do the fabrication. Solarex would identify the environmental, performance, dimensional and other specifications to the commercial fabricator of these systems. In addition, occasional spot checks would be instituted that would verify whether or not production was being conducted on time and within budget and to provide the engineers within Solarex

Figure 3-5 Power Regulator &Controller Fabrication & QA.
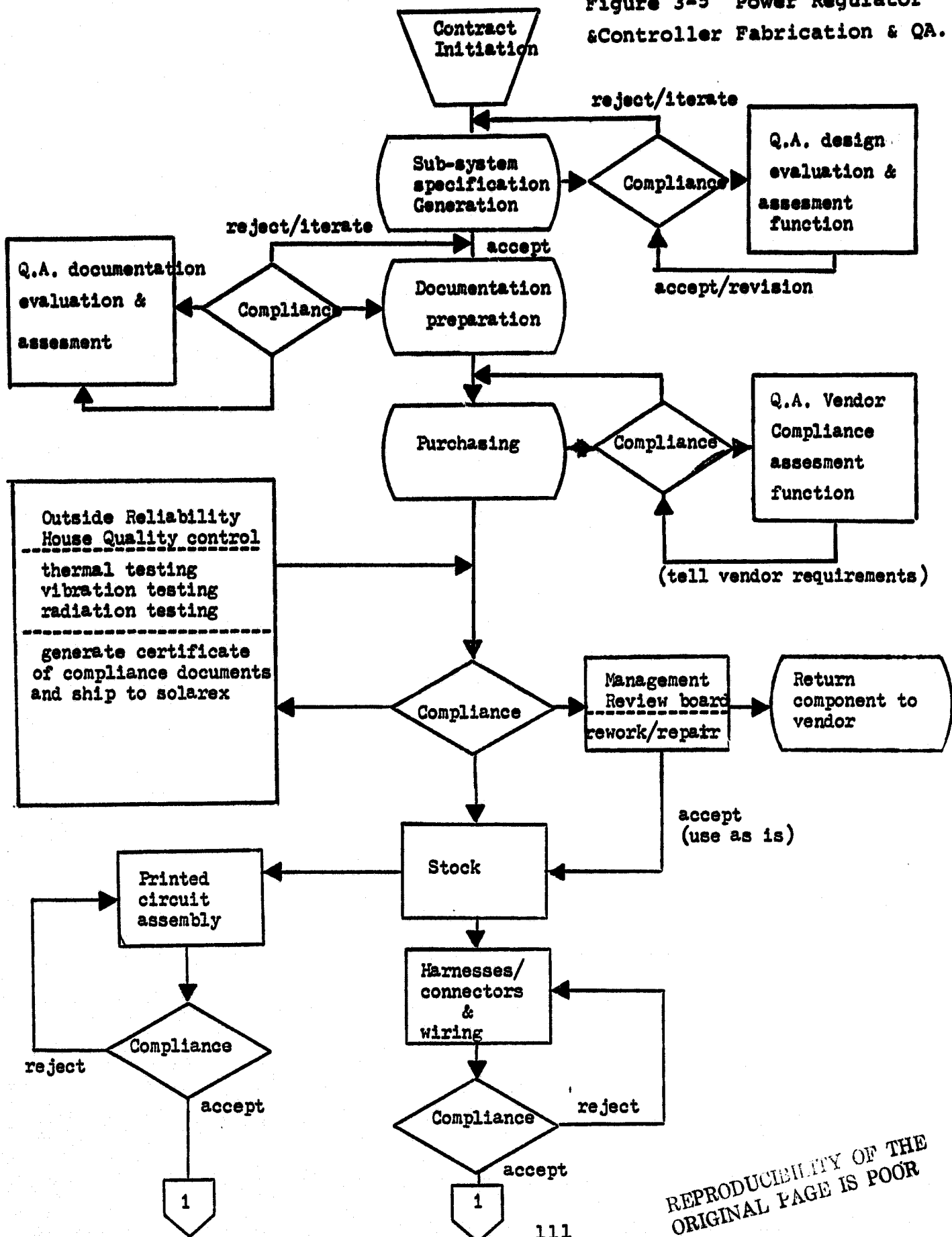
Figure 3-5   (continued)
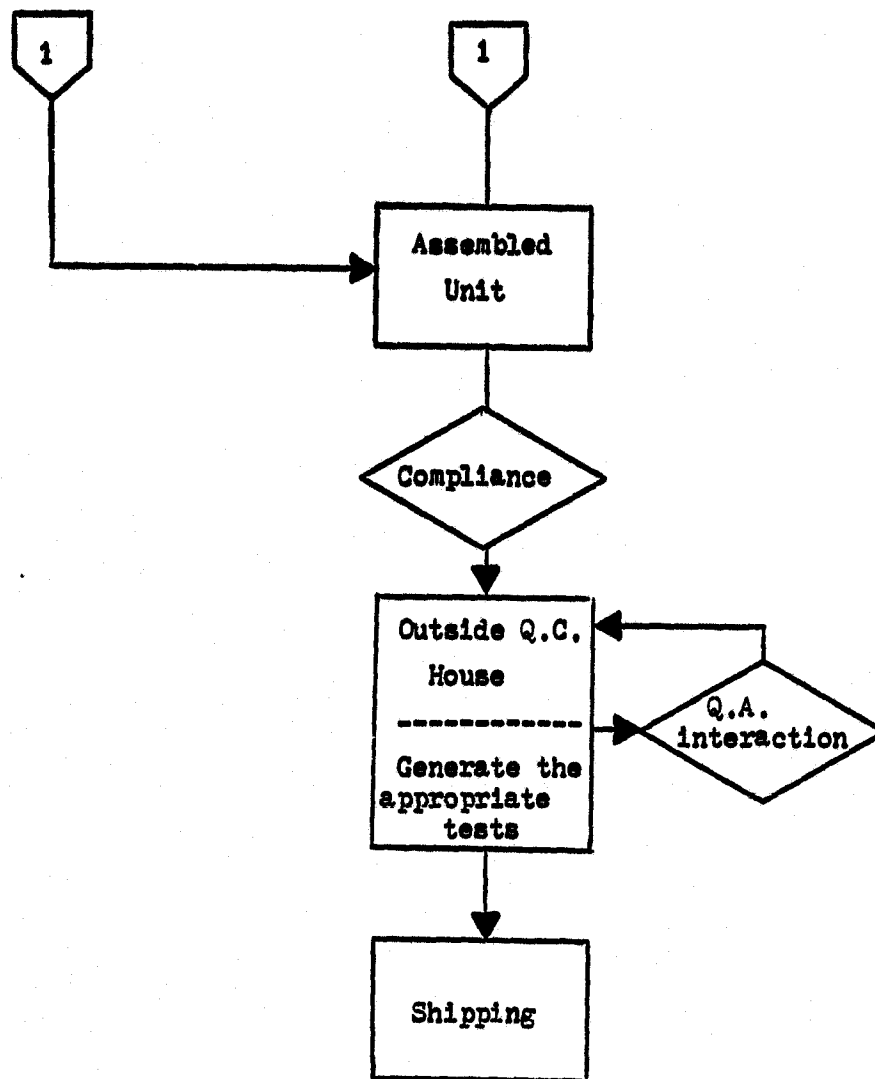
opportunity to interface with the vendor.

3.10.5 Slip Ring and Deployment Assembly

Figure 3-6 gives the flowchart used in the procurement of the slip ring assembly and deployment system. The vendors of both subsystems would follow the design specifications generated by Solarex in the fabrication of these systems.

3.11 Fabrication Manpower/Cost Estimates

The estimated fabrication costs and manpower are detailed in Table 3-9 through 3-12. In this section only the cells, panels, slip rings and deployment fabrication manhours and cost elements are broken out. However, in the case of the battery charge control unit and power regulator the cost and labor of fabricating these units has been tied to the Design and R & QA processes. The reasoning behind this is because the development of such a small set of units does not justify implementing a production approach. Similarly, the cost of the battery containment system is closely tied to development. Only the cost of the aircraft Ni Cd cells is listed as the fabrication cost element.

3.12 Quality Assurance Manpower/Cost Estimates

Tables 3-13 to 3-14 gives the cost/manpower breakdown of each subsystem with the exception of the slip ring and deployment subsystems. For these two systems a percentile estimate was used based on the proportion of Q.A. costs relative to the total cost of hardware. The rationale behind this was that in our attempt at obtaining inputs as to the cost in other

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Figure 3-6
Slip Ring and Deployment Procurement Approach


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          ┌─────────────────┐
          │  Specification  │
          │   Generation    │
          └─────────────────┘
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          ┌─────────────────┐
          │      Bids       │
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          │   Selection     │
          │      of         │◁──────────┐
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          │     Design      │
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          │   Prototype     │
          │   Delivery____  │◁──────────┐
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                   │                     │
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          ┌─────────────────┐           │
          │ Q.A. Analysis   │           │
          │  1. test Q.C.   │           │
          │  2. outside     │           │
          │ test/certification          │
          └─────────────────┘           │
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              ╱─────────╲                │
             ╱           ╲    reject     │
            ╱  Compliance  ╲─────────────┘
             ╲            ╱
              ╲─────────╱
                   │ accept
                  ( 1 )
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Figure 3-6 (continued)

Figure 3-6 (continued)

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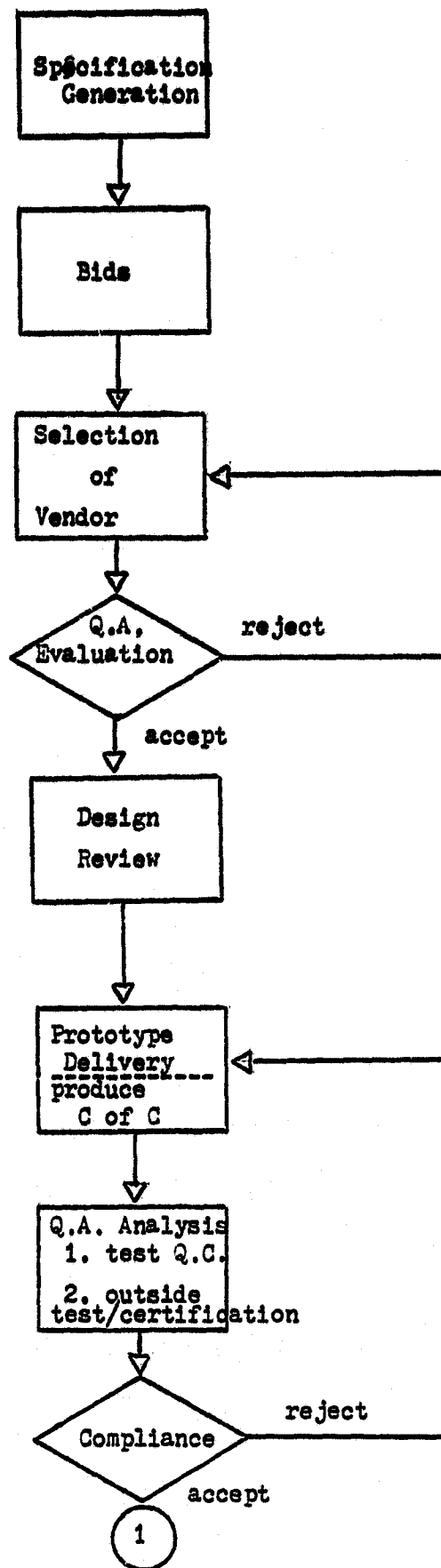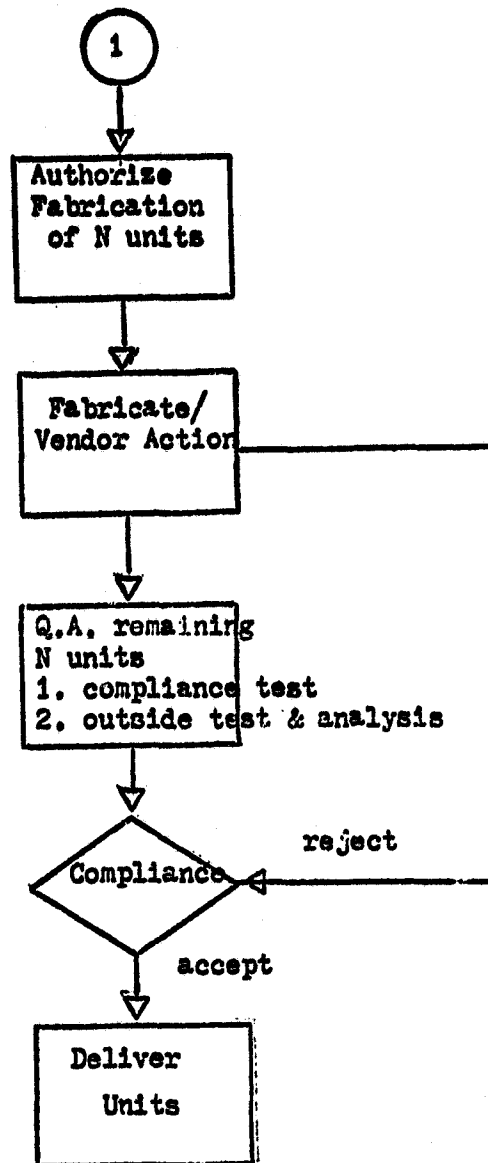
Table 3-9

Cell Fabrication Cost

Task Description	Man Hours	Cost
Straight Processing Labor	3765	$52,377*
Silicon & Materials	----	54,727
	3765	$107,105

* Including overhead charge

Table 3-10

Panel Fabrication Cost

Task Description	Cost
Coverslide (Pilkington's) (ceria doped, cut to order)	$ 69120
A-R Coating (mag. flouride evaporation)	2073
Tabbing Material (uncut)	6579
Sylgard 182/primer	500
Substrate Adhesive	967
Diodes	5279
Honey-Comb Substrate (@ 69 /m^2) 39m^2	2701*
Soldering	276
Labor	13965
Miscellaneous Equipments	7855
Jigs	2995
	$ 112,313

* Cost of substrate varies
   as a function of vendor
   and type of materials.

Table 3-11

Slip Ring Fabrication Cost

Task Description	Price	No.	Cost
Tooling*	7,000	2	$14,000
Engineering*	3,000	2	6,000
Lubrication**			500
			$20,500

*Based on price estimates from polyscientific Corp.
  (Div of Litton Ind.) Blacksburg, Va.

**Based on price estimate from Ball Bros. Corp.

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Table 3-12

Deployment Fabrication Cost

Description	Cost/Item	No.	Price
Electric Drive Motors	$3,500	4	17,000
Extendible Boom	7,000	2	14,000
Lazy Tong Assembly	--	-	12,000
Miscellaneous Engineering and Tooling	5,000		5,000.00
			48,000.00

Table 3-13

Cell Q. A. Cost

Task Description	Man Hours	% Skill Level			
		AP	PT	TA	Sup
Incoming Q.A.	116	.3	1.6 %	22.5%	3.8%
In Process Q.A.	204	1.0	3.9	36.1	3.2
Final Production Q.A.	92	.9	3.3	15.8	7.4
	412	2.2%	8.7%	74.4%	14.4%

Total Cost $ 4,325

Total + Overhead $10,596

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Table 3-14

Panel Q.A. Cost

Task Description	Man Hours	% Skill Level			
		AP	PT	TA	Sup
Tabbing Inspection	95	.5%	1.5%	21.3%	1.0%
Coverglass Q.A	21	.1	.8	3.8	1.6
Intercell Positioning	41	.1	1.0	9.2	.3
Final Visual Q.A.	11	.0	.3	2.0	.1
Performance Test (Flash Simulator)	212.	3.7	13.7	10.26	26.7
Final Q. A.	10			2.04	.5
	390.	4.4%	17.3%	48.6%	30.2%

Total Cost $2,958

Total + Overhead $7,248

Table 3-15

Power Regulator Q. A. Cost

Task Description	Man Hours	% Skill Level			
		AP	PT	TA	Sup
Hardware Design QA and Component Reliability Analysis	120	1.0%	23.3%	3.3%	5.6%
Development & Testing	240	3.3	53.3		10
Total Hours	360	4.3%	76.6%	3.3%	15.6%

Total Cost $3440

Total + Overhead $8430

Table 3-15

Battery Charge Controller Q.A. Cost

Task Description	Man Hours	% Skill Level			
		AP	PT	TA	Sup
Hardware Design Q.A. & Components Reliability Analysis	480	2.1%	32.1%	0%	8.5%
Testing: Electrical Breadboard, Thermal, Radiation, Vibration	640	1.7	37.2	5.7	12.9
Total Hours	1120	3.8%	69.3%	5.7%	21.4%

Total Cost $ 9831

Total + Overhead $2408.

industries--i.e., aerospace companies -- we were unable to identify any real inputs to compute these values.

3.13 Q.A. and Maintenance Cost Relationship

Much can be, and has been discussed about the interrelationship between improving system MTBF and cost of maintenance.[10] One model of this issue is depicted in Figure 3-7 covering the system cost tradeoff with improved reliability. A system characterized by having very high total system cost with a concomitantly high reliability cost and a very low to non-existent failure characteristic (i.e., here described as cost of repairs) is an example of a space qualified approach.

In contrast, in a commercial system the level of R & QA and maintenance relationship which is most economically advantageous to both buyer and builder is where the repairs and reliability costs intersect and where the overall system cost is lowest. At this point on the curve the overall cost of the system is at its lowest and the risk to both the user and manufacturer is least. Some important factors that impact on this are:

- The interaction between quality and cost of repair impacts directly on the system's warranty or service cost. Since the price of warranty is put forth in the selling and service price of the system, the reduction in Q.A. past a certain point would incur a large financial burden onto the builder.
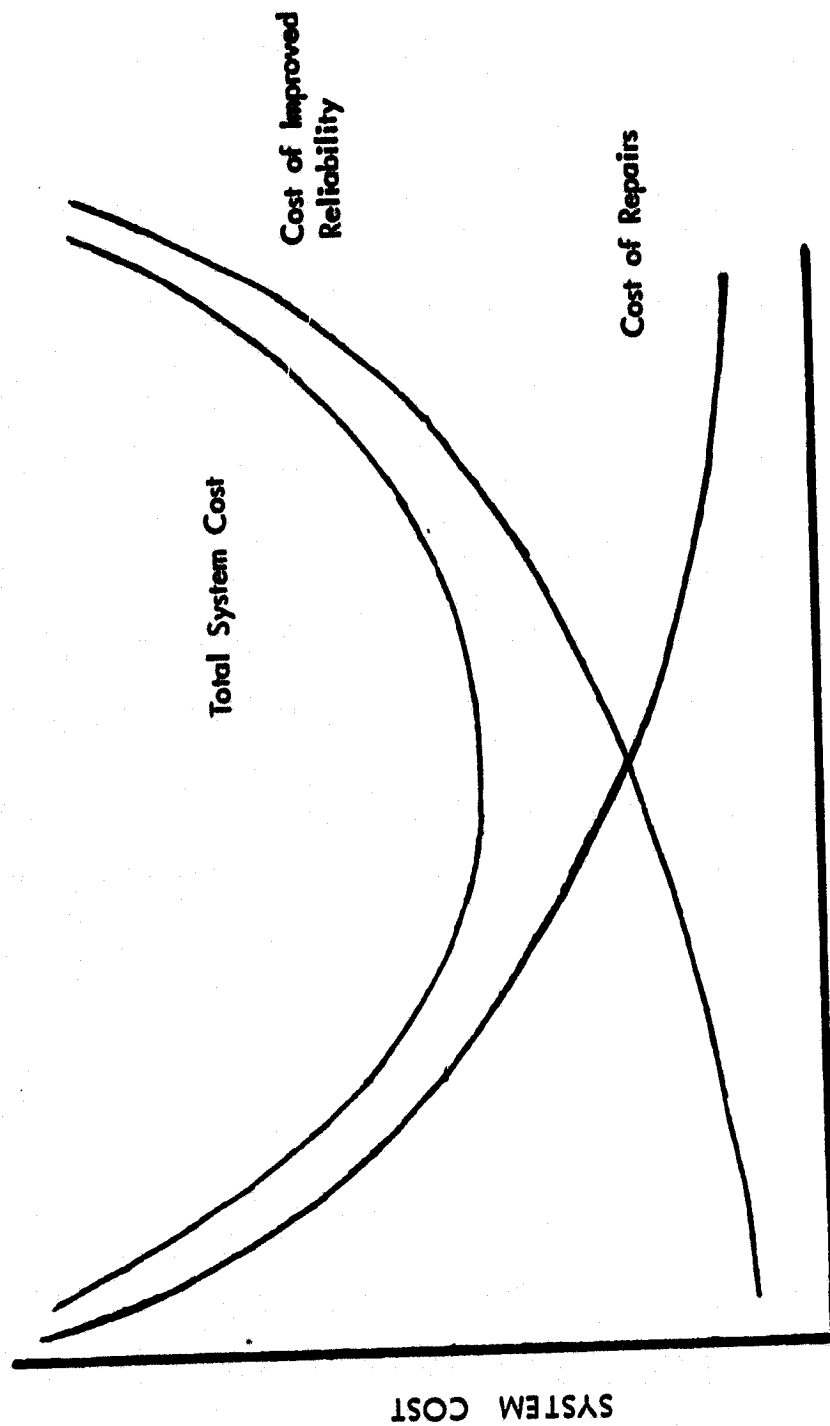
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Figure 3-7   System Cost vs. Improved Reliability Model

- The cost of the greater degree of reliability
  imposes a greater cost risk to the user in the
  event that an actual failure occurs, especially
  if it is non-maintainable. This is because even
  though the likelihood of failure is greatly
  diminished development cost elevates the total
  system cost.

The inclusion or exclusion of certain R & Q.A. functions
must be related back to their cumulative effect on the total
system. Differing systems hold different requirements that
impact on the system and at different points in time during
the fabrication and operation phases of the systems operation
life cycle. The intended approach taken in this study was to
assume that different systems are differentially weighted in
terms of their impact on failure. One example of this was
the battery charge controller. It was viewed by Solarex that
the failure of this system would perpetuate a far greater
degree of compounded failures than that of the other systems.

Another issue to be addressed is the value of the mission
and the system's dependence on continuous operation. This prob-
lem would impact directly on system reliability. A maintain-
able system always accepts the incidence of some level of
failures. If a system is required to achieve a functional
duration of continuous service equal to that of a space
qualified system, the cost of the commercial approach would no
doubt approach or equal a space qualified approach. Therefore,

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no advantage is realized from implementing a commercial
approach at all. The degree of decremental failures (re-
duced performance) and the acceptable frequency of cata-
strophic failures (the system fails to deliver power to load)
must be determined dependent upon mission requirements.
Whether a 2% or 10% chance of failure is realized, some
varying quantity of maintenance operations on the system
must be formalized as a tradeoff between shuttle mission
cost, payload, system downtime and the number of systems in
service. It is suggested that utilization of standard sub-
systems in defined performance ranges for such a power system
would be an important inducement to assist in driving down
cost. Likewise, the greater quantity of comparable systems
and their interchangeability also allows a more promising
future that would reduce the long term maintenance cost of
such systems.

3.14 Materials Cost

Table 3-17 gives a listing of materials costs by sub-
system area. These prices, reflect the cost of major
material components used to fabricate this system. Approxi-
mately 40% of this system's cost is associated with materials
and hardware. The two systems yielding the smallest proportion
of materials cost to overall cost are the power regulator
and charge controller. In contrast, the cell and panel
system reflect a large amount of required materials for
their production and development.

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Table 3-17

TOTAL SYSTEM MATERIALS COST

Cells.	$ 52,377
Panels	$ 98,348
Slip Rings	$ 14,500
Deployment . . . . . . (Motors)	$ 17,000
Booms.	$ 14,000
Lazy Tong Assembly	$ 12,000
Power Conditioning . .	$ 3,500
Charge Control	$ 6,000
	$223,230

3.15 System Integration and Qualification Testing

The final system checkout would entail a two part approach. Initially, when the subsystems are fabricated they would be brought together for assembly and bench testing. Here the configuration control manager would take charge of connecting and inspecting the assembly. As the different systems are interconnected they would be inspected for tolerance and conformity. At this point discrepant connectors or methods used would be removed for repair. If the change is minor a spot fixup would be instituted at the bench test site. This process would require either purchase or rental of needed equipment in order to properly test the operating system and qualify all assembly of the subsystem parts. After the bench test of the completed power system is concluded, the second part of the system test would be conducted.

Because Solarex is a commercial venture it would be necessary to subcontract to an aerospace firm to perform a final qualification test. We were able to identify the cost required to conduct such tests. The system would be handed over to the aerospace firm to perform operation of the system under a vacuum environment with a dummy load attached to the system which would run through a fast checkout of the system under altered electrical loading

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and temperature conditions. Measurements such as outgassing and thermal inertia of various subsystems would be taken. Following this, the system would be evaluated, modified and sent on to its next destination. Such testing would be held to a minimum because of the high cost of operating such systems.

A cost breakdown (Table 3-18) of final integration and qualification testing indicates that the final testing using a vacuum simulator chamber would be a major cost driver of this function.

Table 3-18

SYSTEM INTEGRATION AND QUALIFICATION TESTING

Task Area	Cost
Documentation of Testing Regime for Bench Testing and System Qualification Testing, Documentation of Test Procedures	2000
Test Equipment Purchases and Rentals Estimate	5000 and above
System Integration Inspection	5000
System Integration Operation Test	2000
Vendor Supplied Qualification Testing	80000
	$ 109,000

4.0 Cost Summary and Evaluation

4.1 Cost Summary and Approach Overview

This study comprises a substantial philosophical shift
in approach for developing a space power system. It
is evident from the preceding section that the emphasis
is directed away from extensive documentation and quality
assurance in order to reduce the management overhead
typically associated with these systems. In addition,
this study also points out that from a commercial viewpoint,
producing such an item should be performed with a minimum
of waste in both materials and labor. Major items to be
stressed are the following:

- Solar cell production -- The production of photo-
  voltaic cells must be kept at an economically
  competitive level. The fabrication of such devices
  must be oriented toward making maximum use of the
  major production cost driver, silicon. Maintaining
  volume production throughput also reduces cost.

- Panel system production -- The fabrication approach
  implemented in this study is not geared for production
  cost savings as evidenced by comparing a commercial
  panel with the one configured for this system.
  That is, a commercial Solarex high density panel
  (priced in lots of 100 units @ 37 W/panel) cost is $576,

yielding a cost per watt of $15.50. In contrast, the 28W panel configured for this study costs approximately $1840, a per-watt cost of $66. This difference in cost is largely due to the small volume of systems made, environmental and weight constraints and added labor for quality assurance. This difference also means that with volume demand and product standardization of the panel/array, cost can be reduced over time.

- Battery system production -- This system's cost can be reduced by employing the strategy for acceptance testing and the battery system recommended in Section 3. However, if this approach is unacceptable the transition to space qualified batteries would not produce a significant increment in the overall power system cost. The approaches derived in this study suggest further investigation into this area.

- Systems development -- The approach implicit in this study is an alternative method of prototyping this system. Prototyping is mainly relegated to the verification of a subsystem's functioning. For a limited production situation, extensive testing of subsequent duplicate components is a substantial cost burden which, from a commercial standpoint, should

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be minimized. In sum, provision should be made to make maximal use of materials and labor by reducing, if not eliminating, full scale backups or proto-types if they cannot be directly useful.

In many cases the long standing emphasis on acquiring maximal reliability and product sophistication has formed a predisposition to sell advancement in technology, which has increased cost. Such an emphasis carrys with it an array of reasons which justify the cost from a traditional space quali-fied approach. Historically, this approach has been justified in the light of the space programs successes. However, this does not constitute a sufficient precedent for future appli-cations.

4.2 Full System Cost Estimation

Table 4-1 shows a final breakout of costs derived for the four major subcategories of this study (i.e., design, documentation, fabrication and R&QA). As noted in Table 4-1 the fabrication cost of the batteries, charge controller and power regulator reflects only hardware costs. This is due to the developed nature of these systems. In the case of the slip rings and deployment systems the cost estimates reflect inputs from vendors and from cost estimating

Table 4-1

System Cost Estimate

	Design	Documentation	R&QA	Materials	Fabrication	Total
Cells	$ 5,600	$ 2,965	$10,596	$54,727	$52,377	$126,265
Panels	$13,595	$ 3,602	$ 7,248	$98,348	$13,965	136,758
Battery	$15,944	$ 7,509	$12,300[1]	$10,000	---	45,753
Battery Charge Controller	$47,952	$ 6,662	$24,086	$ 6,000	---	84,700
Power Regulation	$13,713	$10,885	$ 8,430	$ 3,500	---	36,528
Deployment System	$16,400	$ 4,354	$10,000[2]	$43,000	$ 5,000	78,754
Slipping[?]	$20,102	$ 3,063	$ 8,000[2]	$14,500	$ 6,000	51,665
Qualification Testing			$109,000			109,000
Miscellaneous Cost	$133,306	$40,733				
		$ 1,693				1,693
	$189,660	$230,075	$77,342			

Total Cost = $671,116

NOTE:
1-- Acceptance Test Plan
2-- Estimated R&QA

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exercises conducted inhouse. The cost structure of Table
4-1, when broken out by these four categories, gives the
following percentages:

Design..........................24.3%

Documentation................... 7.1%

R&QA............................15.8%

Fabrication.....................52.8%

The mix of cost percentages varies widely from system
to system as depicted in figure 4-1. As this plot shows,
the greatest spread in costs is in the design and fabrication
areas. It is of interest to note, as indicated in Figure 4-1,
that the cell and panel subsystems required the smallest per-
centage of total system cost for design, documentation, and
R&QA while requiring the largest percentage of total cost for
fabrication. In contrast, the battery charge controller
required a large initial design percentage of total cost with
the smallest percentage for fabrication.

4.2.1 Manpower

Table 4-2 gives a breakdown of manpower estimates for
all systems. As shown, the spread of manhours varies widely
from system to system and category to category. Here too,
as with system cost, these values reflect the different
emphasis in production involved in each subsystem. The total
manhours presented in Table 4-2 yields an estimated 7.5
manyears required to develop such a system. This figure does
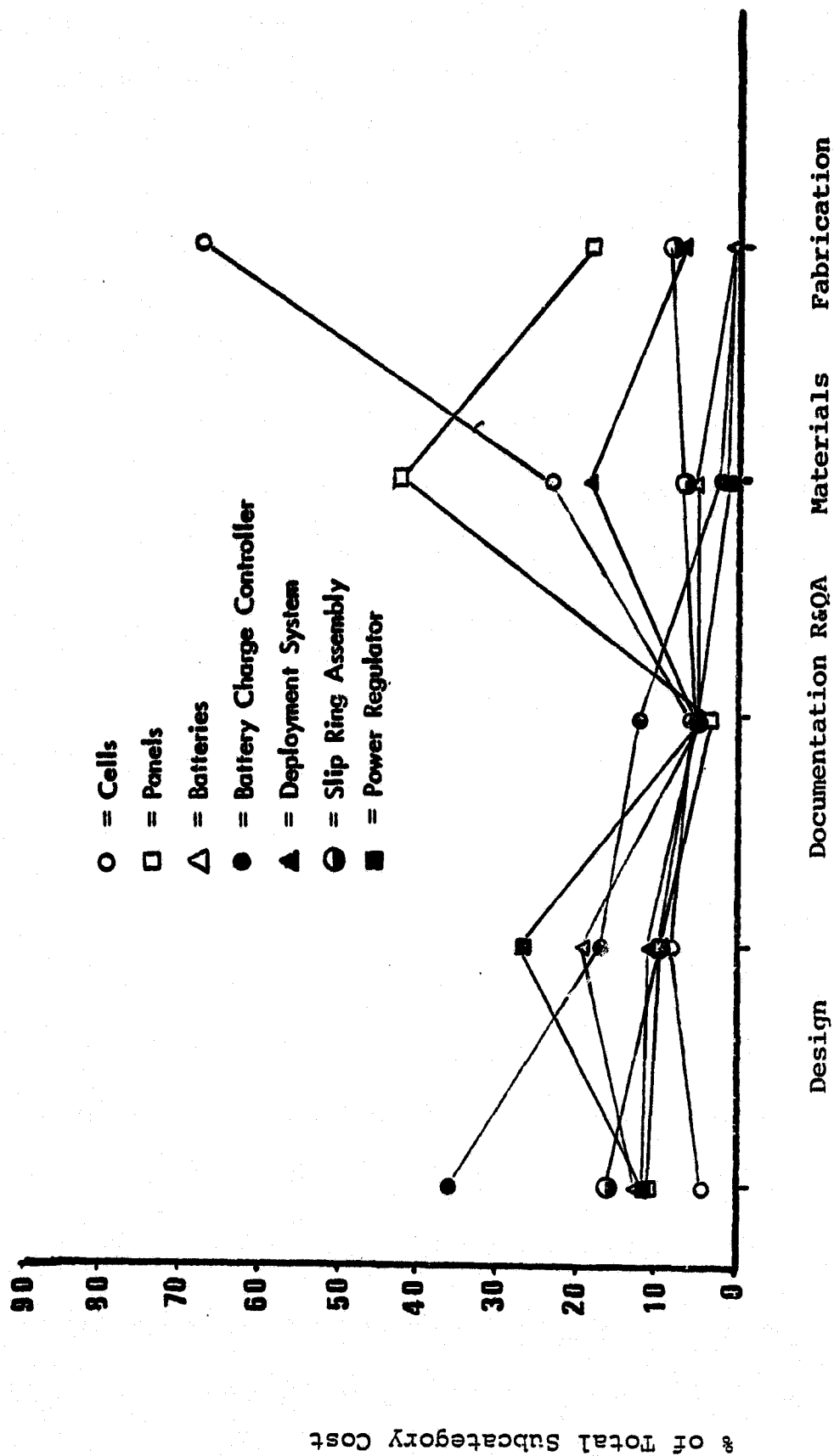not address the issues of qualification testing and system

Figure 4-1   Comparative Plot of Subsystems by Category

Table 4-2

(Hours)

MANPOWER ESTIMATES

	Design	Documentation	R & QA	Fabrication
Cells	295	132	412	3,765
Panels	595	165	390	420
Batteries	720	280	668	—
Battery Charge Requirements	2277	329	1120	—
Power Regulation	744	610	360	—
Deployment	738	270	—	—
Slip Ring	730	180	—	—
	6089	1966	2950	4185

TOTAL: 15,250 Hours

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checkout, which would elevate the manpower and cost over that which is presented in this study.

It is important to consider the mix of skill levels required to build the system. In a commercial approach the production level should be of sufficiently large scale to take advantage of low skill levels. In estimating manpower and cost this will be a large part of the total system cost. At present all photovoltaic manufacturing is considerably labor intensive. Manpower and subsequent cost still remain a significant component in the overall cost of fabricating a cell. Proportionately the manhours required to develop a new cell design and or process technology is quite small. With the other systems the labor component becomes even greater. This is all due to the custom nature of the system. Without the development of improved mass production and assembly methods, cost will not diminish much. This is of special importance for solar cells because their cost is much greater than that of the other subsystems.

4.3 Cost of Multiple Copies

Typically the nonrecurring cost of a system would not be shared with the recurring production cost. The removal of nonrecurring cost will yield a 24% overall reduction in system cost. However, in a commercial venture this cost is usually amortized over many copies of the system. Figure 4-3 shows the cost reduction that could result from fabricating multiples of this system. Following an initial
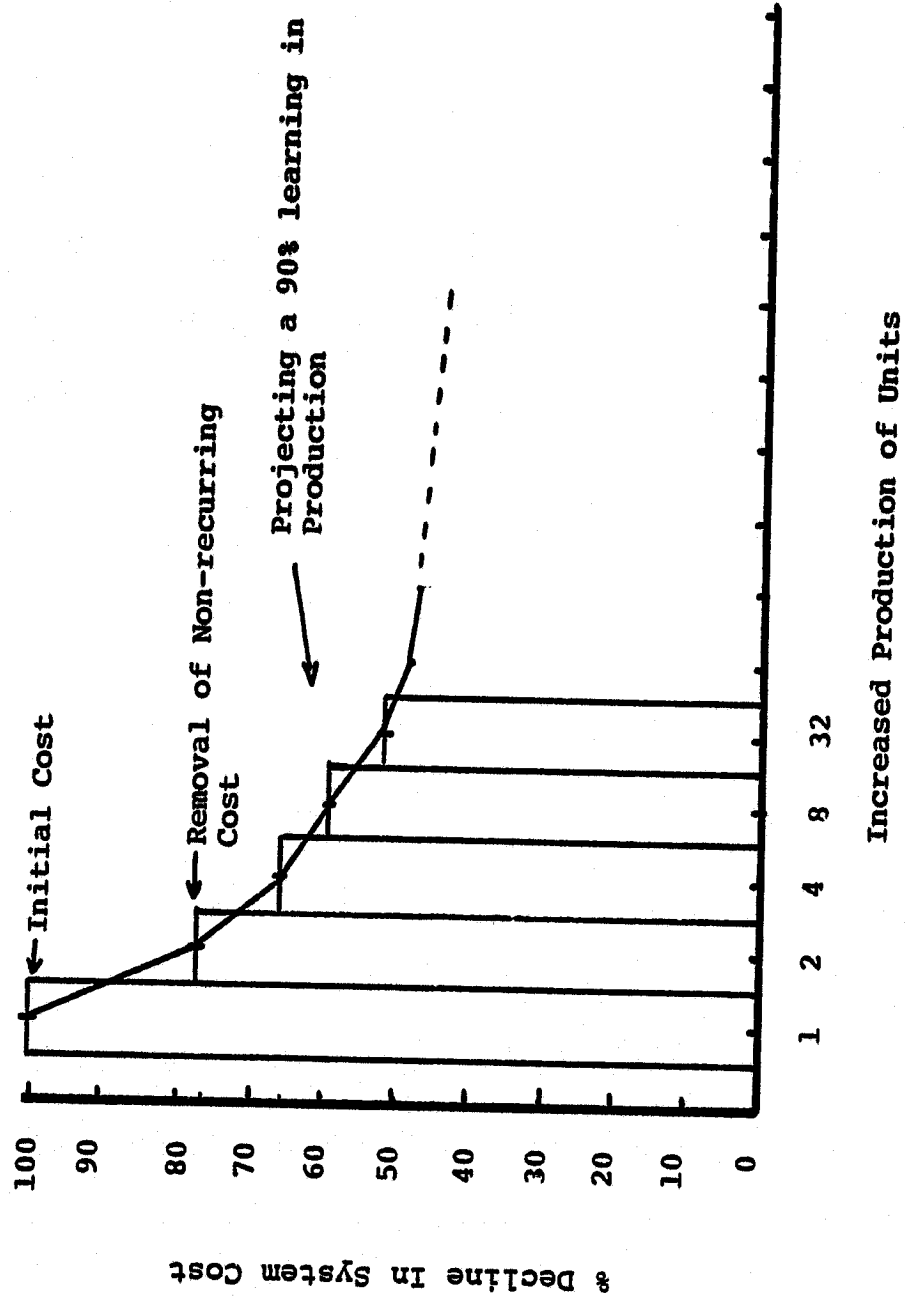
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Figure 4-3   Projected Cost Reduction As a Function of
Increased Number of Units Produced

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elimination of nonrecurring cost factors and fitting a 90%
learning curve to subsequent copies (i.e., the cost of each
successive iteration of producing a system is 90% of the cost
of the previous system for each doubling in the number produced),
the overall system cost may be reduced substantially. This
is a conservative estimate of reducing production cost.
However, other space related costs such as repairs, and
transportation may tend to reduce this overall cost savings.
In addition, the impact of alternate production methods may
yield significant reductions in labor cost, assuming the pro-
duction of large numbers of duplicate systems comes about.
A guaranteed long term market for such systems would undoubtedly
spur a manufacturer to develop cost reducing production
techniques and equipment.

4.4 Warranty Cost

As previously presented in sections 3.4.5 and 3.4.6, a
warranty can take on a wide range of characteristics depending
upon what it is needed for. Typically, the cost of a warranty
is based on an analysis of the systems failure characteristics
(as addressed in section 2.2.1), both theoretical and observed,
fabrication and quality assurance tradeoffs that were made
(as discussed in section 3.10). From all of these various
inputs the manufacturer must determine the cost to his company
to replace or repair failed components. Because of this study's
exploratory nature a detailed analysis and estimation of war-
ranty cost is beyond the scope of this study.

A typical industry standard warranty charge is usually
about 10% of the system's cost per annum. Similarly a 90 day
unconditional warranty is likewise based on the fractional
cost of the 10% warranty charge added to the initial price.
In this case if we assume that the cost of transportation is
not a risk to the manufacturer, and given the untried nature of
this approach, the best and simplest approach would be to perform
all repairs on an 'at cost' basis.

4.5 Servicing

Terrestrial photovoltaic systems are inherently designed
to be modular and repairable. Unlike the space qualified
approach, i.e., enforcing high reliability, redundancy and
quality assurance, a terrestrial photovoltaic power system by
definition is assumed to have the characteristic of being
broken down into modular segments which can be manually
removed and repaired. A review of what approaches have been
taken into consideration in this study will point this out:

- The array wing is designed to be composed of individual
  panels or modules with the expressed intent of being
  replaceable.

- The charge controller and power regulator are separable
  modules so that if one or the other fails both do not
  require replacement.

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- Drive motors for the slip ring and deployment assemblies are intended to be disconnectable, in the event of a motor failure.

- The slip ring brush assembly is considered to be a separable module which can be disconnected and replaced as needed.

Designing and fabricating systems that have the capability for servicing assumes some level of effort over and above a baseline system, just as the added design required to develop redundancy and increase reliability. However, to apply a numerical estimate to this added effort requires an investigation of the space qualified approach and the commercial approach starting from a preestablished baseline system design. Here one can only estimate that 5% of the cost to design is associated with developing servicing capability.

4.6 Concluding Remarks

The present study has examined both technical and economic aspects associated with the design, development and production of a "commercial" 2KW space power system.

Given the economic and technical factors considered by this study; the development and production of such a system is technically feasible and economically advantageous. The major data supporting the system's economic advantage are summarized below in Table 4-3. Table 4-3 gives a finalized cost breakdown comparing

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the present study's "commercial" power system with an equivalent "traditional space-qualified" one. It indicates a relatively uniform diminuation in cost across all the major subsystems, with the completed "commercial" system costing about one quarter of the space-qualified system's price.

Table 4-3

Finalized Cost Breakdown

Category	Space-Qualified[11]	Commercial
Solar Array	$1,500K	$263K
Batteries	180K	46K
Power Processing	360K	121K
Mechanical Systems	225K	130K
System Integration & Qualification	400K	109K
	$2,665K	$669K

The cost estimation process used in this study has been predicated on the basis of in-orbit serviceability. This concept serves as the basis for the following recommendations:

- Use larger solar cells for more cost-effective use of materials, manpower and present technology.
- Use battery systems founded upon avionic approaches with modified containment and charge-discharge schemes.

- Use proven space-qualified designs and hardware where commercial/terrestrial analogs do not exist.

- Avoid non-standard custom-built components.

- Relax specifications and avoid production philosophies which require an excessive Quality Assurance labor force.

- Clearly define pass/fail decision points in the production process, thereby avoiding duplication of effort and repititious testing.

- Avoid exhaustive product/component classification and documentation.

- Emphasize performance over cosmetic criteria for acceptance testing.

- Limit process control documentation detail. If sufficient, use already existant documentation.

- Promote and maintain manufacturing throughput, maintain company cash flow and reduce inventory.

- Promote contiguity of demand. Smoothing out demand stabilizes production activity and the production labor force.

- Practice conservation and reclamation of silicon in the production environment, since silicon accounts for over 50% of solar cell cost.

- Minimize usage of capital-intensive facilities which are not cost-effective. One case in point is the use of clean rooms.

- Use prototype components and/or subsystems as parts for the final flight version. In most instances the prototype and flight version would be one in the same.

Potential areas for follow-on effort with respect to developing economical space power systems include:

- Further comparison of an "economical/commercial" vs "space-qualified" serviceable power system to the extent of design and development of two equivalent systems.

- Build and flight-test a power system using the methods and approaches suggested in this study.

- Further study the feasibility of developing criteria for standardizing space power systems for a wide variety of space applications.

References

1

F. J. Cepollina and J. Mansfield, _In Orbit Servicing_, Astronautics and Aeronautics, Vol 13, No. 2, 1975

2

Future Orbital Power Systems Technology Requirements, NASA Conference Publication 2058, A Symposium Held at Lewis Research Center, Cleveland, Ohio, May 31 and June 1, 1975

3

Solar Cell Radiation Handbook, National Aeronautics and Space Administration, JPL Publication 77-56, 1977

4

Reliability and Maintainability Training Handbook, Prepared by General Dynamics/Astronautics, 1964, NAVSHIPS 0900-002-3000.

5

D. Fortney, Solarex In House Research Memoranda, 1978.

6

Solar Cell Array Design Handbook, National Aeronautics and Space Administration, JPL SP43-38, 1976.

7

Nickel-Cadmium Battery Application Engineering Handbook, General Electric Company, Publication Number GET-3148A, 1975.

8

Ernst Cohn, Energy Storage Consultant to Solarex, See List of Contacts, 1978.

9

C & D Battery Co., Product brochure.

10

J.P. Solomond and G.A. Marseglia, _Cost Optimizing System to Evaluate Reliability_, In, Proceedings 1977 Annual Reliability and Maintainability Symposium, IEEE Catalogue Number 77CH1161-9RQC.

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F. Teren, 'An economical Approach to Space Power Systems', p. 269, _Future Orbital Power Systems Technology Requirements_, NASA Publication 2058, 1978.

Appendix A

Person/Organization	Subject
Ernst Cohn; Battery Systems expert; consultant to Solarex corporation	Battery system design and acceptance testing approach. A substantial portion of Mr Cohn's suggestions are incorporated into this report concerning use of batteries.
General Electric Co./Gainesville Florida, technical sales staff for space and aircraft batteries	Information on Ni Cd batteries: 1. Cost 2. Encasement 3. Price range and performance ranges of G.E. Ni Cd's
Naval Weapons Center/Crane Indiana (Donald Maines)	Information on Ni Cd test data. 1. Cycle efficiency 2. Amp-hour ratings
Gates Energy Products	N/A
Gould Inc.	N/A
Union Carbide	N/A
Ford Aerospace/battery systems group (Ronald Haas)	Battery performance; 1.System testing procedures 2.Cell energy characteristics 3.Cycle life 4.Discharging and Reconditioning approaches.

Person/Organization	Subject
Eagle-Pitcher	Space Qualified battery cost estimates
Marathon Batteries	Aircraft batteries cost estimates

Person/Organization	Subject
Ball Brothers Co (Jim Hendricks)	1. Space Lubrication methods 2. slip ring costs 3. Designs and configurations 4. Materials and approaches 5. Supplied literature on space qual products
Inland Motors (Gary Young)	Deployment motor costs
Ford Aerospace (Don Briggs & Dennis Killian)	Deployment system costing
TRW/ Al Rosenburg Power Systems group	1. Slip ring development cost 2. Life testing 3. Specification and engineering practice 4. Prescribed voltage drop 5. Effects of vacuum welding
Polyscientific Co(Div of Litton industries)	1. Slip ring Machine design 2. flat cable design 3. Duplication of design in both axes to cut cost 4. Estimation of engineering and tooling cost 5. Voltage and current requirements

Person/Organization	Subject
Boeing Aerospace Co (David Jones; Head of Space Simulation Laboratory)	1. Cost estimation of vacuum testing 2. Discussion of contractual requirements to perform work.